MOVING STRIATIONS IN AN ARGON GLOW DISCHARGE

EUGENE A. PELTON
and
HENRY C. NORTH, JR.

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Eugene A. Pelton

Lieutenant Commander, United States Navy

and

Henry C. North, Jr.

Lieutenant, United States Navy

Submitted in partial fulfillment of
the requirements for the degree of

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IN
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ABSTRACT

Moving striations in a direct current argon glow discharge were studied over a pressure range from 11 mm of mercury to 200 microns of mercury and over the current range from 25 ma to 0.13 ma. Striations were found present at all pressures and currents, and the striation patterns observed were divided into four general regions with patterns becoming extremely complicated at the lower pressures.

A disturbance in the positive column which seemed to originate at the cathode and propagate toward the anode was studied extensively using rotating mirror photography, an oscilloscope in conjunction with photomultipliers, and a spectrograph. Attempts were made to identify this disturbance as a negative striation, but it did not fit the characteristics or the descriptions offered by other investigators nor did it depend in any simple way upon the glow discharge parameters.

Several times during the course of the investigation it was thought that striations had been eliminated, but by greatly increasing the mirror speed, very fast moving striations were detectable. Other interesting phenomena which were observed include the modulation of a slow moving wave with a very high frequency, high velocity striation. When possible, rotating mirror photographs and photomultiplier output traces are shown which illustrate the phenomena observed.

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1. INTRODUCTION

1.1 History

Moving striations, the term describing alternate bands of darkness and luminosity travelling through the positive column of an inert gas glow discharge, were first discovered by Abria (1) in 1843. Although this phenomenon has been known to exist for approximately 120 years, no adequate theory explaining the striations has been proposed to date. Perhaps the reason experiments are difficult to correlate is that all the parameters influencing the striation movement are not known and that seemingly identical experiments are actually quite different. Since parameters such as tube geometry, purity of gas, structure and material of the filaments and shields all affect the striation velocity, frequency, and wavelength, it is not surprising that many conflicts occur in the literature on gas discharges.

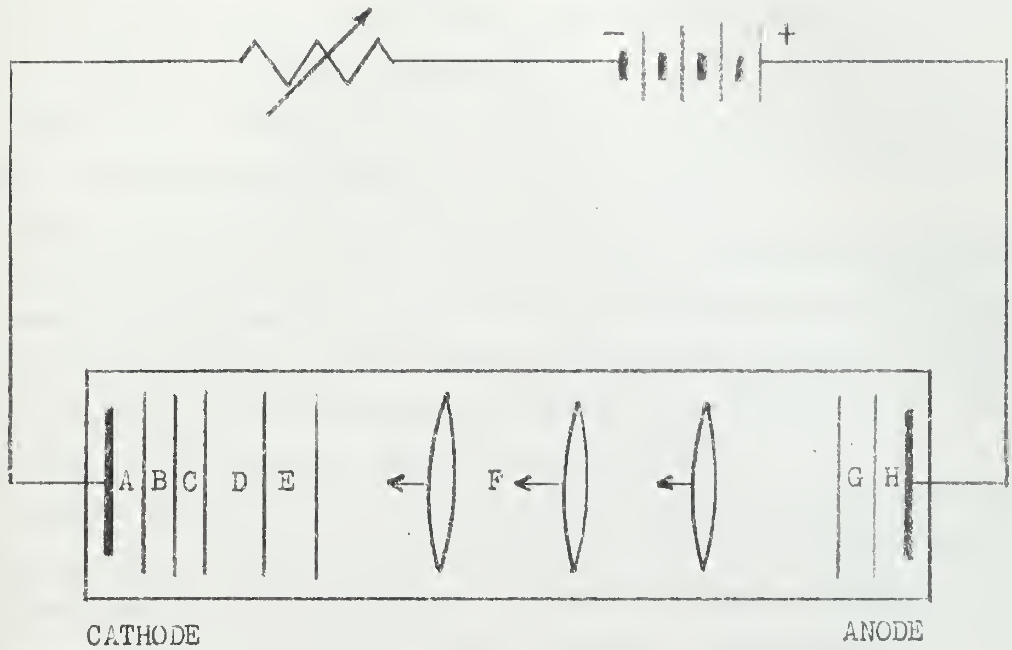
1.2 Characteristics of a Glow Discharge

When the gas pressure in a discharge tube is reduced to less than several centimeters of mercury, an applied voltage causes a current to flow through the gas which in turn produces a uniform glow throughout the tube. This glow discharge as described by von Engle (2) is a discharge in which the cathode emits electrons under the bombardment of particles and light quanta from the gas.

When a direct current glow discharge is established in a long cylindrical tube filled with a rare gas at about one millimeter of mercury, the visible light emitted from the discharge is distributed over the length of the tube as shown in Figure 1. The lengths and relative light intensities of the characteristic regions of the discharge are dependent upon the tube geometry, gas pressure, applied voltage, discharge current and type of gas present.

1.3 Previous Theoretical Work

There have been many attempts to formulate a theory to explain the presence and predict the behaviour of the moving striations, but no such theory has yet been elaborated which is completely in agreement with the known experimental facts.



A. Aston Dark Space

B. Cathode Glow

C. Cathode Dark Space

D. Negative Glow

E. Faraday Dark Space

F. Positive Column

G. Anode Glow

H. Anode Dark Space

Figure 1 A Glow Discharge (3)

Gordeev (4), in an excellent theoretical paper, was able to show that when thermal scatter of particle velocities is considered in the problem of the excitation of high and low frequency plasma oscillations by a beam of charged particles, the stationary state of the plasma and the beam is unstable. He showed that a plasma can be excited by a low velocity electron beam at the expense of the energy of the electrons which must be replaced by the electric field. Thus, the state of the plasma with undamped high-frequency plasma oscillations in a constant external field is stable. Gordeev went on to show that if the excitation of the plasma is done by an ion beam, the undamped low-frequency oscillations, the phase velocity of which is less than the thermal velocity of the ions, are also stable.

Gordeev (5) in an earlier paper postulated that both positive and negative moving striations are a direct result of electron oscillations. The positive striations are a wave group initiated by electrons changing velocity in the anode fall. The negative striations are reflections of the positive striations in the negative glow or at the cathode.

Donahue and Dieke (6) also believe that oscillations and moving striations are almost always present whenever a positive column exists in inert gases and mercury glow discharges, and the rare cases in which striations are absent should be considered the exceptions. They suggest that moving striations have a principal role in sustaining a glow discharge. The positive striations are regions of high positive potential space charge which travel toward the negative glow. The negative striations are the result of a burst of electrons which were trapped in the negative glow but are permitted to escape when the potential barrier is lowered due to the approaching positive striation.

Watanable and Oleson (7) show that there can exist, in a positive column, traveling waves of ion and electron density. They do not identify these waves as moving striations. They establish mathematically the possibility of these moving density waves existing in the positive column by use of the diffusion equations. The equations were linearized by the assumption of a small perturbation on the steady charge density with variations of second and higher orders neglected.

Robertson (8) approached the problem by assuming that all space dependence can be eliminated in a uniform positive column. The continuity equations then assume the form $\mathring{Y} = G - L$, where Y is the appropriately averaged concentration of electrons, positive ions, or metastables, $\mathring{Y}$ is its time derivative, G is the production rate of the component Y, and L is its loss rate. At equilibrium $\mathring{Y} = 0$ and upon solving the equations for the three components of interest, assuming constant current density and that the electron mobility is independent of the field, he was able to show that metastable-dependent plasmas can be unstable under certain conditions, and he suggests that these instabilities might be the cause of moving striations.

This led him to the investigation of the continuity equations with Z dependence but radial currents considered still part of the loss terms. By including the divergence term in the continuity equation and assuming that $Y = Y_o + Y_o \exp(\Gamma t + KZ)$, he was able to arrive at a consistency determinant which was extremely complicated. In making further approximations to simplify the equations to be solved, Robertson showed that his results did not agree with the experimental results reported by Donahue and Dieke (9).

Although Robertson's approach has many weaknesses, it is interesting in that it attempts to explain the presence or properties of striations as due to the properties of the plasma itself; whereas other theoretical papers study the response of a column to an applied perturbation.

Yoshimoto, Sato, and Nakao (10)(11) describe an experiment on moving striations in an arc discharge, and they attempt to explain the phenomena by a theoretical paper on space charge waves. They visualize a light intensity wave which is the product of the field intensity wave and the electron density wave. It is assumed that the electron density wave is its equilibrium value plus a sinusoidal dependence on time, and that the electrical longitudinal wave is its equilibrium value plus a sinusoidal dependence on time and position. The product of the two waves gave a light intensity equation: $\vec{L} = \overrightarrow{L(X)} + L_o\vec{A}(t) + L_o\vec{B}(X,t)$. The light intensity equation was then differentiated with respect to time to find the time when it was at its maximum value, and the maximum light intensity remained a function of X and t.

They found that under certain conditions, the maxima of the light intensity oscillations appeared nearly at the same time throughout the entire positive column, and those phase differences are shown as a periodic function of X. According to their theory, in such a case moving striations will not appear and the striations seem to move periodically back and forth according to the X chosen. Under certain different conditions, moving striations were predicted to appear all the time and seemed to follow the results obtained experimentally by the same authors. They claim that the assumption of a light intensity wave explains all the experimental results and establishes the characteristic properties of the standing and moving striations.

Pekarek, using a method of artificially induced transitory processes, has produced several notable theoretical and experimental papers. Starting with a discharge which is on the edge of spontaneous emergence of oscillations and moving striations but at the same time where there is as yet no self-oscillation and where the positive column is completely homogeneous, Pekarek uses an external short term disturbance which destroys the equilibrium of the discharge and leads to the temporary appearance of consequentiality in all those processes which under different conditions indicate self-excitation, i.e., the current is modulated in such a manner that the positive column goes from a homogeneous, stable plasma to one with striations present. The transitory disturbance produces waves which Pekarek describes as waves of stratification. These waves of stratification move from cathode to anode and are of two types fast and slow.

Based upon his experimental observations, Pekarek (12) proposes the existence of two feedback loops which can be responsible for the initiation of the two types of waves of stratification. He hypothesizes that the fast waves of stratification are the result of direct ionization of atoms by electrons and the slow waves are the result of step-by-step or cumulative ionization. The results of his experiments to determine the influence of external illumination on moving striations in a discharge in neon appears to support the concept that slow waves of stratification are produced with the participation of step-wise ionization while a fast wave of stratification is produced as a result of direct ionization (13).

Robertson (14), using irradition from an external source of the same gas, observed transient damped oscillations in the tube voltage, and he identifies these damped oscillations with those reported by Pekarek (12) as resulting from applied voltage pulses. Robertson demonstrated the dependence of moving striations upon metastable atoms in the positive column plasma of a glow discharge by experiments in alkali metal vapors, which have no metastable states and no moving striations, and by experiments in the inert gases, where the metastable population and the striation behavior can be greatly changed by the technique of irradiative depopulation.

In a theory on the successive production of moving striations in inert gases the stratification of the discharge is interpreted by Pekarek as the successive production of regions of alternately positive and negative space charge (15). These alternate regions of space charge represent the macroscopic periodic polarization of the plasma. Pekarek assumes relative independence of the chain of processes in each region of the striations so that interaction between the regions occurs as a result of the electric field of the space charge in the neighboring region.

Pekarek used small perturbations in formulating this theory and points out the value of using transient rather than steady state processes. He says that the use of transient processes permits the determination of five independent parameters: the velocity of propagation of the wave of stratification from cathode to anode, the velocity of striations, lifetime of the nth striation, spatial period of striations, and the ratio of maximum amplitudes of neighboring striations. Only two independent parameters can be determined for steady state processes. Pekarek also states that two other important properties of the transient process with small perturbations are linearity and the fact that only processes occurring in regions of the discharge inside the positive column have to be considered.

The theoretical predictions made in this paper are verified with one exception in a later report (16). He reports that the exception is represented by the larger packet widths observed experimentally for the fast waves of stratification. The reason given for the difference between the theoretical prediction and the experimental results is the difference between the actual and the theoretical initial conditions. The actual perturbation did not correspond to the form of a Dirac function.

As a follow up to statements that he had made earlier with regard to feed back loops (12), Pekarek further proposes that several factors influence the self-excitation of low frequency oscillations and the production of moving striations (17). These factors are:

1. The tendency of the plasma to stratification,
2. The length of the positive column,
3. Processes in the regions of the electrodes,
4. The external circuit.

In this same paper Pekarek gives experimental evidence to support these proposals and concludes that the tendency of the plasma to stratification is most important. The tendency of the column to stratify depends on the type of gas, the pressure, the current, and the diameter of the tube.

It is also in this paper that Pekarek reports finding the region in a neon discharge without self-excited oscillations. He used a tube 0.55 cm in diameter, 60 cm long with an indirect cathode. Measurements were made in the current interval 1.2 ma to 30 ma and in the pressure interval from 2 to 10 mm of mercury. He observed a non-striated glow discharge in the pressure range from 3.6 to 10 mm of mercury within the current interval 1.2 to 3.8 ma. Figure 2 is a reproduction from his paper showing the area of interest.

In a very recent paper Pekarek (18) gives an interpretation of the physical nature of the production of striations. His interpretation is based on the mathematical expression of the production of periodic structure in a plasma after an aperiodic disturbance. He includes only three basic phenomena in the mathematical formulation: (a) the dependence of the rate of ionization on the electron temperature and hence the electric field, (b) the production of space charges due to different rates of diffusion of the electrons and ions, and (c) the creation of additional electric fields due to the creation of space charges. This theory, as he points out, does not explain the time dependent properties of the wave of stratification nor does it solve the problem of amplification and damping of the wave of stratification. He says its main value lies in the determination of the decisive physical processes which lead to moving striations in the positive column of a direct current discharge and in the explanation of the basic mechanism of the successive production of striations.

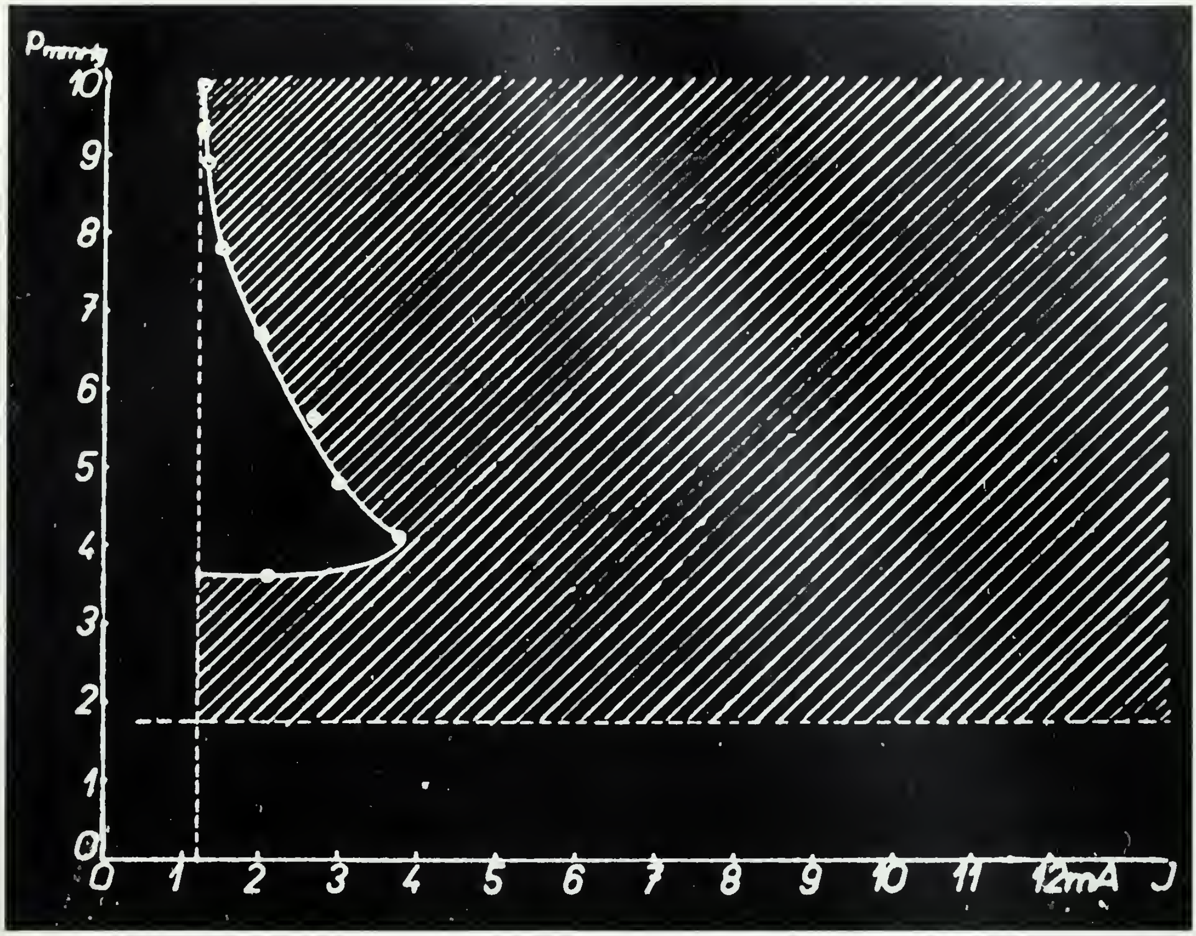


Figure 2 - Reproduction of Pekarek's pressure verses current plot in a neon glow discharge. The hatched area represents the region of self-excited low frequency oscillations. The clear area is the region without oscillations in the discharge. The tube diameter for this experiment was 0.55 cm. and the tube length was 60 cm.

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In a paper delivered at the Fifth International Conference on Ionization Phenomena in Gases, Pekarek studies the effects of a more exact formulation of the dependence of the rate of production of ion pairs on the mean kinetic energy of the electrons and thereby also on the intensity of the local electric field (19). This paper is principally an elaboration of results derived previously (18).

1.4 Previous Experimental Work

A complete summary of the early experimental observations on moving striations was published by J.J. Thomson (1), and a summary of the more recent experiments is covered in the monograph by Emeleus (20). These studies of the moving striations were made chiefly by means of rotating mirrors, although Pupp (21), who has published a series of five papers, also used a photo cell in conjunction with a cathode ray tube.

Donahue and Dieke (6) published a paper describing a survey of the properities of moving striations. Their investigations of the light intensity of the striations were made by a photoelectric method similar to that of Pupp, with the exception that they used the tube voltage oscillations to syncronize the oscilloscope sweep and they used only one photomultiplier. Donahue and Dieke felt that they were able to detect on the photomultiplier negative striations moving from the cathode to the anode.

Zaitsev (22) described an experiment using neon, neon and argon, and air in tubes 80 cm long with different diameters. He was able to produce moving striations with a magnet and he sometimes observed negative striations.

Zaitsev (23) in a later paper, described an experiment using pure neon in a cold cathode tube of unpublished length. He reported seeing two oscillations of different frequencies in the discharge tube which appeared to produce beats under natural conditions of discharge without the action of an external force. He also noted a hysteresis effect in entering and leaving the auto oscillation mode. Zaitsev states, toward the end of his report, that there is a close connection between the stationary and moving striations in a discharge; and he was able to conclude that a discharge with moving striations is of a form intermediate between stably uniform and stably striated discharges and may make a transition to either of these stable forms.

Oleson and Cooper (24), working with neon glow discharge at several mm of pressure, found that the frequency of the moving striations could be changed considerably by altering the anode-cathode distance. The frequency appeared to be a roughly periodic function of the anode-cathode distance, and cathode movement caused greater change than anode movement.

Coulter (25) in a very recent paper described an experiment using pure neon in a tube 2.5 cm in diameter and 108 cm long. He reported the splitting of the normal striations as they approached the Faraday dark space from the anode. This branching occurred in such a way as to make it appear that a negative striation was interacting with the normal positive striation for approximately 40 microseconds. This disturbance apparently is localized at the head of the positive column at lower pressures, and can be observed somewhat further towards the anode at higher pressures.

Coulter, Armstrong, and Emeleus (26) conducted an experiment using a tube with two different radii. They were able to conclude that moving striations can originate at oscillating anode spots. However, they did not show that anode spots are necessary for the existence of moving striations.

Rodemacher and Wojoczek (27) have described a series of experiments on striations in cross-shaped discharge tubes at low pressures in argon. They reported that it was impossible for them to eliminate moving striations when naturally present, and they concluded that perhaps the presence of moving striations is necessary for the existence of the long positive column in an argon discharge in a certain range of current and pressure. In the high current region, Rodemacher and Wojoczek agree with Pekarek (17) that cathode disturbances spread into the discharge more easily than anode disturbances.

Cooper (28) has described in detail a multitude of experiments which were done by him in an attempt to determine the origin of moving striations and the limiting criteria for their existence. No attempt will be made to comment on all variations of parameters made by Cooper, but the section on lower critical current for moving striations will be discussed as it is particularly pertinent to this report.

Cooper states that the lower current limit for the existence of striations was studied only for one set of operating conditions in a cold cathode discharge using a tube of diameter 2.5 cm and length 20 cm filled with argon at 12 mm of Hg. He found no low frequency fluctuations in the light intensity

for a current under 14 ma, and rotating mirror photographs indicated that striations had been eliminated. Upon increasing the current, he found an intermediate region from 14 ma to 38 ma where striations occurred at irregular intervals. Upon further increasing the current above 38 ma, he reports regular striations in the entire column.

Cooper is reluctant to conclude anything on the basis of one set of operating conditions, but states that it appears that as tube current is increased from low values, striations appear progressively from the anode end of the positive column.

2. EXPERIMENTAL PROCEDURES AND EQUIPMENT

2.1 Vacuum System

A schematic diagram of the vacuum system is shown in Figure 3. The system was designed by A.W. Cooper and is the same type used by him in earlier moving striation investigations. This particular system offers considerable flexibility and versatility since tube changes can be made rapidly and tubes of different lengths and diameters can be accommodated.

2.2 Vacuum Techniques

The system was evacuated by a two-stage oil diffusion pump and a fore pump. The pumps in conjunction with the liquid nitrogen traps were capable of bringing the vacuum system down to pressures of approximately 10^{-7} mm of mercury. High vacuum measurements were made with a Consolidated Electrodynamics Corporation Ionization Gauge, type GIC-110 with a VG1A sensing tube. Pressures in the millimeter range were measured using a manometer filled with Octoil-S diffusion pump oil.

Several steps were taken to insure that a high purity discharge was investigated. The discharge tube was baked at a temperature of 400°C for approximately twelve to twenty-four hours in a portable, thermostatically controlled oven. The metal surfaces within the discharge tube were degassed using an induction heater manufactured by the Scientific Electric Company. The filaments were cleaned by resistive heating. In the terminal phase of the purification process the discharge tube was filled with argon, the discharge was ignited, and then the tube was slowly evacuated until the discharge was extinguished. This step was repeated several times.

2.3 Discharge Tube and Electrode Configuration

The discharge tube was constructed locally in the tube laboratory by John Calder, the Postgraduate School Glass Blower. The electrode assembly was constructed by Robert Moeller, the physics department machine shop operator and was patterned after the electrodes first discussed and demonstrated experimentally by Pupp (29) to eliminate the positive anode fall and the associated oscillations. An all metal Alpert type valve capable of bake out was used to isolate the discharge tube from the rest of the vacuum system.

VACUUM SYSTEM

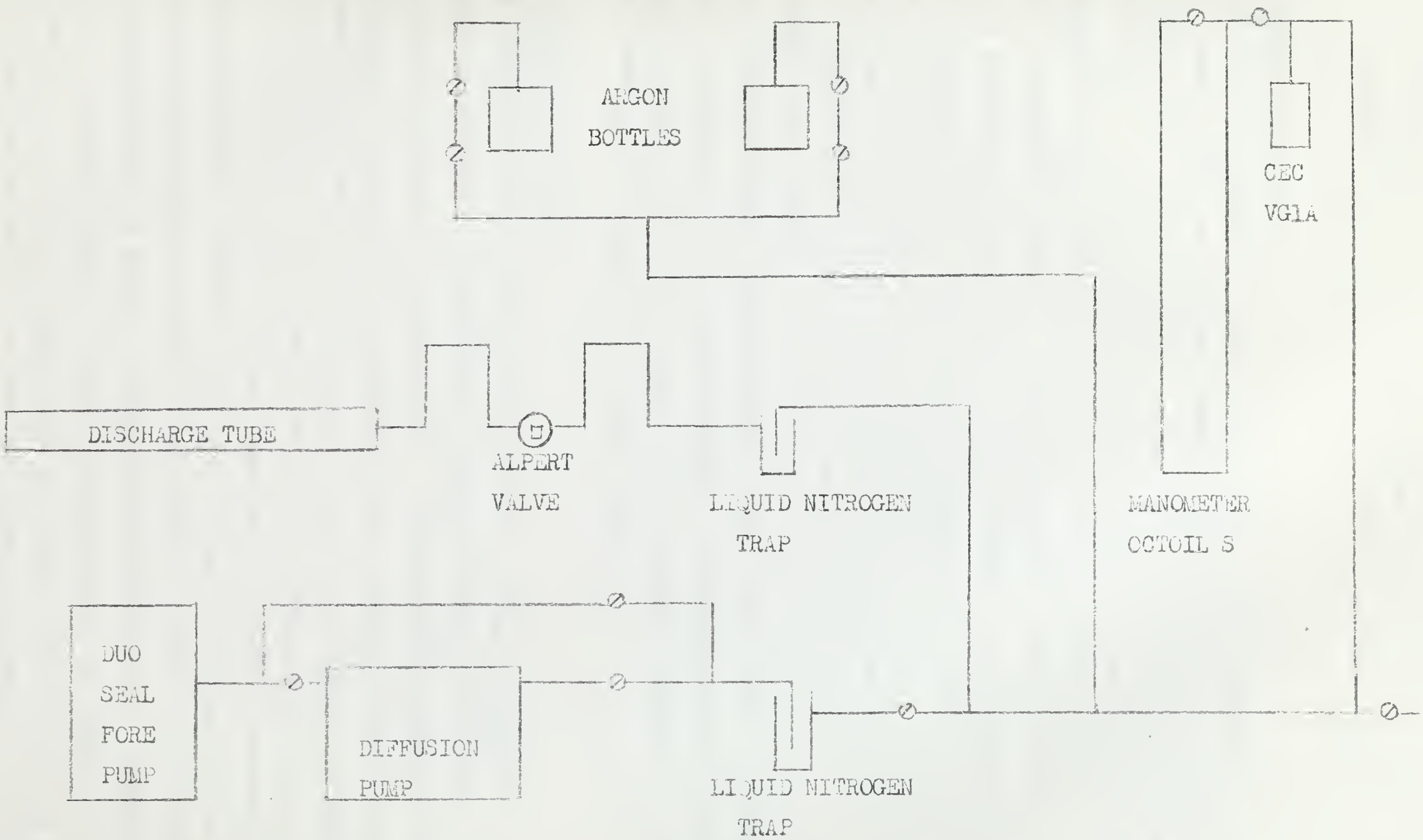


Figure 3

A diagram of the tube and the electrode configuration is shown in Figure 4. This particular electrode design was utilized in order to be able to operate either end as a heated cathode or a Pupp anode.

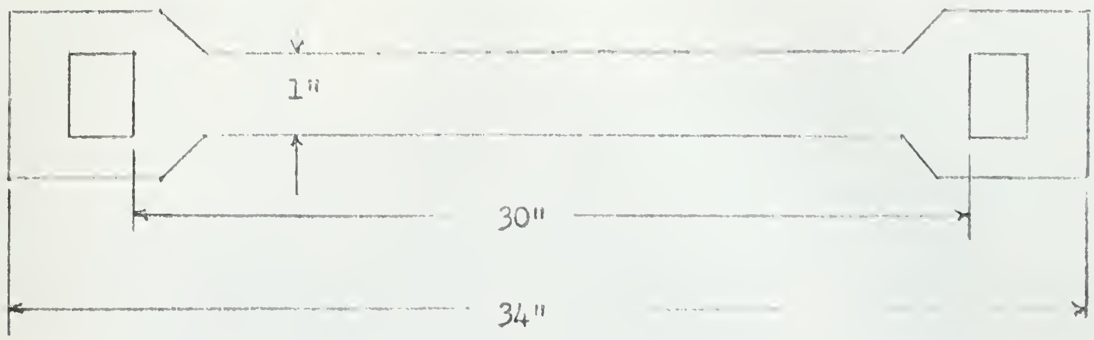
2.4 Electronic Circuit

A schematic diagram of the circuit used is shown in Figure 5. The high voltage power supply was a Kepeco Model 1250B with a range 0-500 milliamps and 0-1000 volts. The resistance in the circuit could be varied from 0 to 768,700 ohms. A variable capacitor and an inductor, which are not shown in the schematic diagram, were used in the circuit at various times. The capacitor, connected in parallel with the discharge tube, was used in an attempt to stabilize the discharge, and the inductor, connected in series with the discharge tube, was used to determine the effects of an inductance on the striation parameters and the generation of streaks. The streaks, a sporadic set of disturbances which appeared to move from cathode to anode, will be described in detail in another section of this paper.

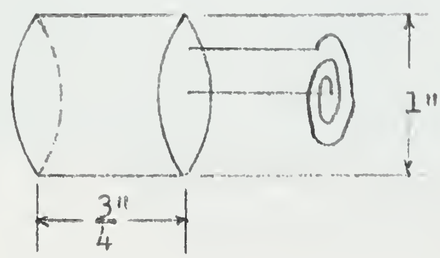
When it was necessary to operate an auxiliary discharge for a Pupp anode, a Sorensen Model 1000-88 Nobatron with a range 0-750 milliamps and 0-1200 volts was used for the power supply. A Kepco Model KM 236-15A with a range 0-15 amps and 0-50 volts was used to heat the filaments in phases of the investigation requiring a heated cathode.

2.5 Measuring Equipment

A photograph of the experimental set-up is shown in Figure 6. The discharge parameters of interest were measured with a milliammeter, voltmeter, oscilloscope and rotating mirror. The Weston 622 ammeter offered the advantage of being able to measure currents varying from 0 to 1000 milliamps without having to interrupt the electrical circuit to change scales. An RCA WV-98B vacuum tube voltmeter was used to measure discharge tube potential. A Tektronix Model 551A Dual Beam Oscilloscope in conjunction with two photomultipliers (RCA 1P21) was used to measure the amplitude and wavelength of moving striations when the discharge was stable. The frequency of the striations for a stable discharge was measured using a Hewlett-Packard Model 521 electronic counter. When the discharge was not stable, the rotating mirror was used for velocity and wavelength measurements. A photograph of the rotating mirror and associated camera equipment is shown in



DISCHARGE TUBE



ELECTRODE CONFIGURATION

Figure 4

ELECTRONIC CIRCUIT SCHEMATIC

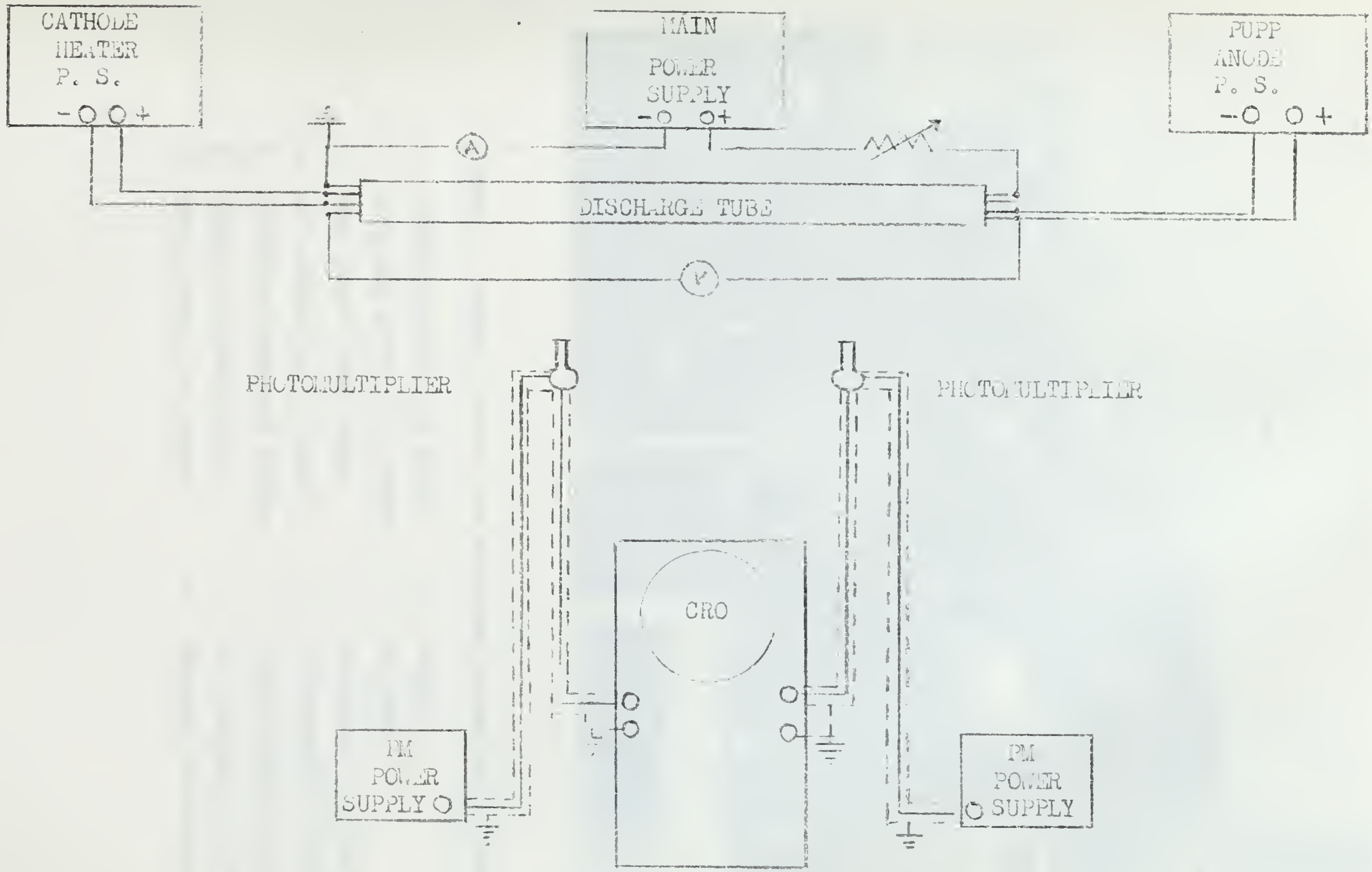


Figure 5

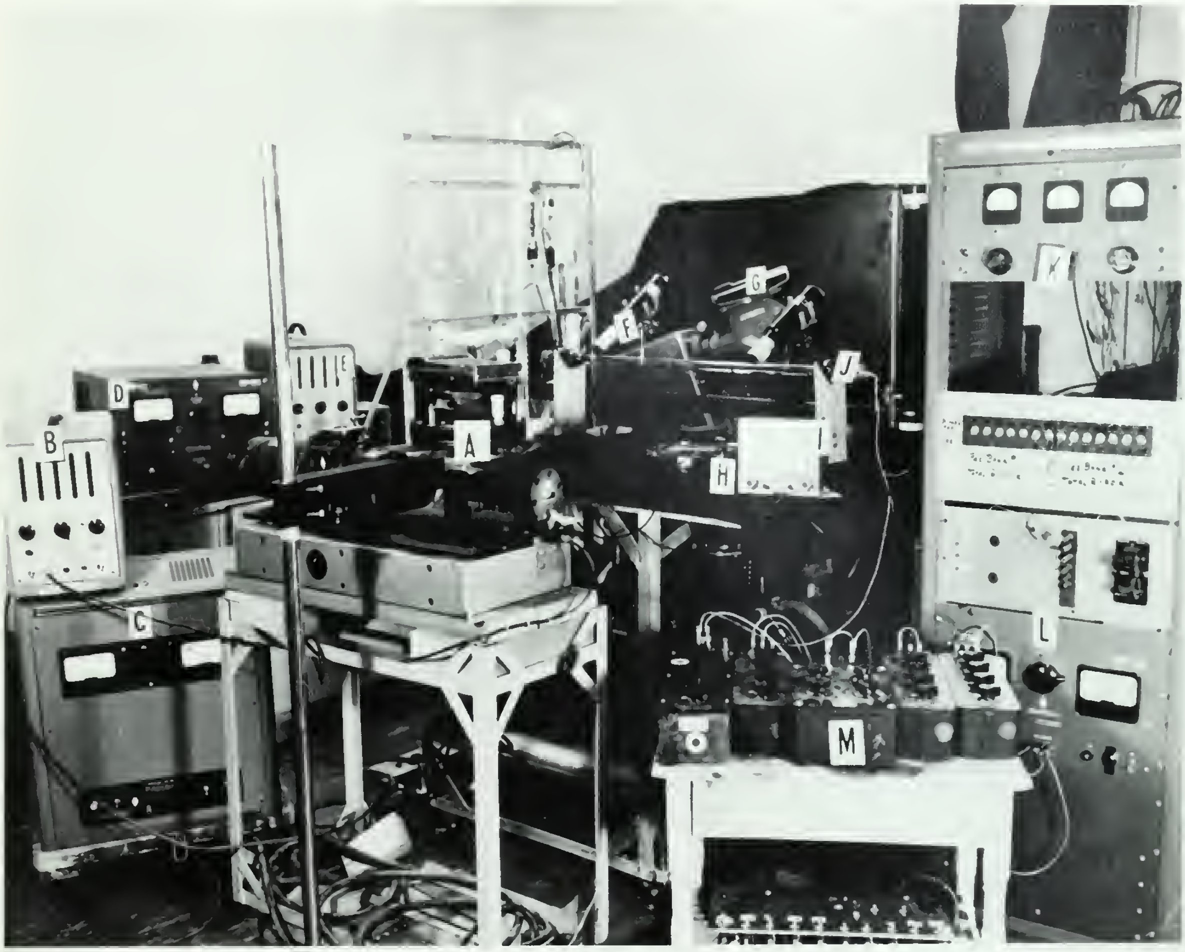


Figure 6 - General view of the operating system and accessories

A.	Rotating mirror and camera	H.	Ammeter
B.	Rotating mirror RPM counter	I.	Voltmeter
C.	Pupp anode power supply	J.	Discharge tube (anode end)
D.	Hot cathode power supply	K.	Photomultiplier power supply
E.	Striation frequency counter	L.	Main discharge power supply and external resistance bank
F.	Cathode Photomultiplier		
G.	Oscilloscope and camera	M.	External resistance bank # 2

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Figure 7. The mirror which has dimensions 4" x 6" x 1" is made of stainless steel. One surface of the mirror is polished and is coated with a thin film of aluminum. The mirror can be driven at any speed varying from 0 to 9250 revolutions per minute.

2.6 Wavelength Measurements

The wavelength of the moving striations was measured by two different methods when possible. When the discharge was stable, it was possible to measure the wavelength using two photomultipliers, one at a fixed position along the discharge tube and the other moveable parallel to the tube. The sweep was triggered either externally by the voltage oscillation of the discharge tube or internally by one of the two photomultipliers whichever gave the smoothest trace. The output of the photomultipliers was displayed on the dual beam oscilloscope. When the two photomultipliers are separated by an integral number of wavelengths along the discharge tube, the two output traces appearing on the oscilloscope are in phase. As the mobile photomultiplier is moved the traces on the oscilloscope go out of phase and do not return to an in phase display until the mobile photomultiplier has traveled a wavelength along the discharge tube. By mounting the mobile photomultiplier on a track with a centimeter scale it is possible to measure the moving striation wavelength directly.

When the discharge was not stable and also as a check on photomultiplier measurements described above for a stable discharge, rotating mirror photographs were analyzed to determine the wavelengths of the moving striations. Figure 8, which is a rotating mirror photograph, illustrates how the moving striation wavelength was measured. The dark lines across the face of the photograph are calibration marks on the discharge tube which are a known distance apart. In the photograph time increases upward and a horizontal line drawn through the photograph indicates the conditions in the discharge at any particular time.

2.7 Frequency Measurements

The frequency of the moving striations was determined in two ways. It could be measured directly for a stable discharge by having the photomultiplier output trigger a frequency counter. For an unstable discharge it was

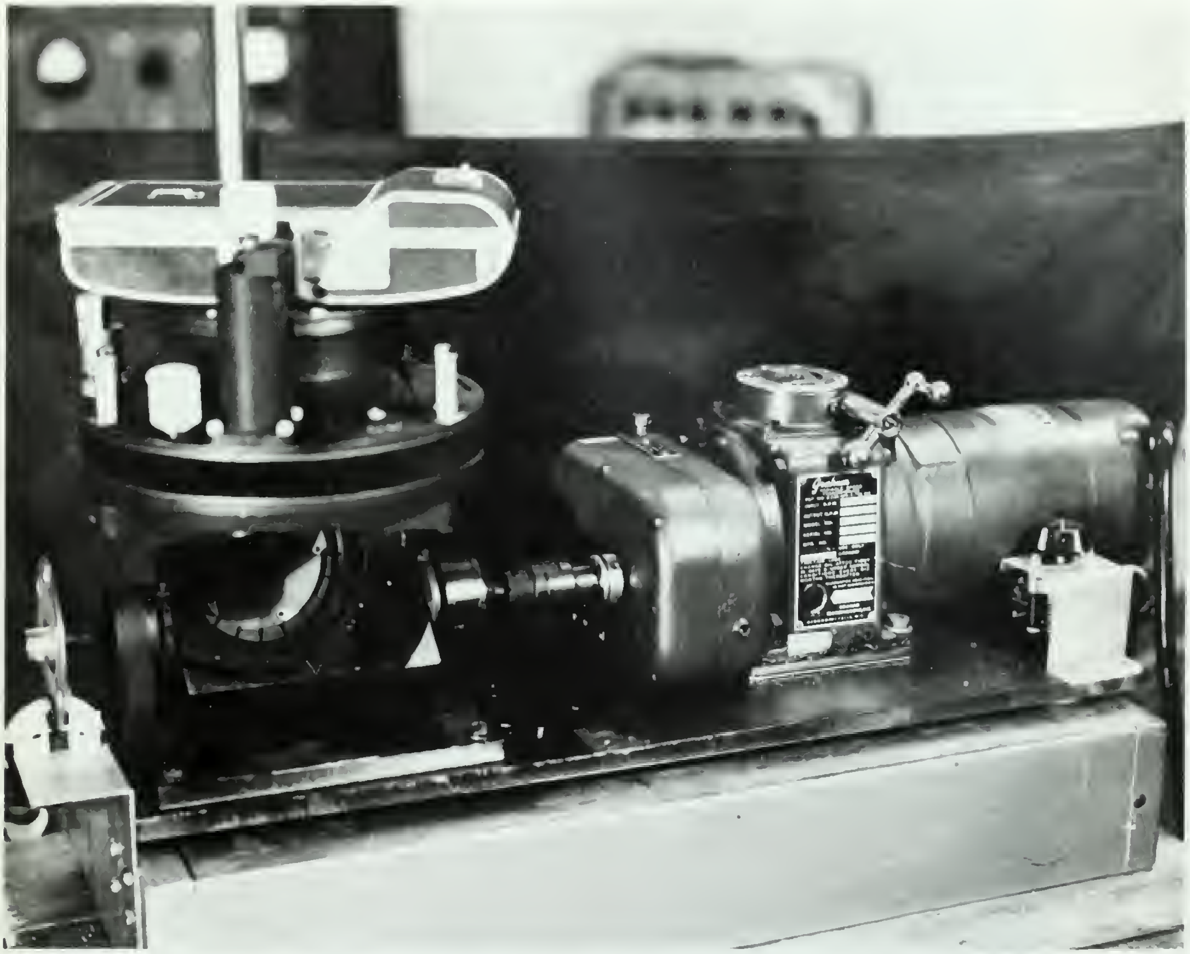

Figure 7 - Rotating mirror and mounted camera assemblies

The rotating mirror assembly includes:

a. Electric motor - Marathon Electric, Mod. VE.

b. Graham variable speed transmission - 3450 RPM input; 0 to 9250 RPM output.

c. Mirror - 4" X 6" X 1" solid stainless steel with evaporated aluminum on polished surface.

The camera assembly includes:

a. Fairchild (manually operated) shutter type K-38

b. Auto Topcor 1:18 lens

c. Polaroid land camera back type 2620

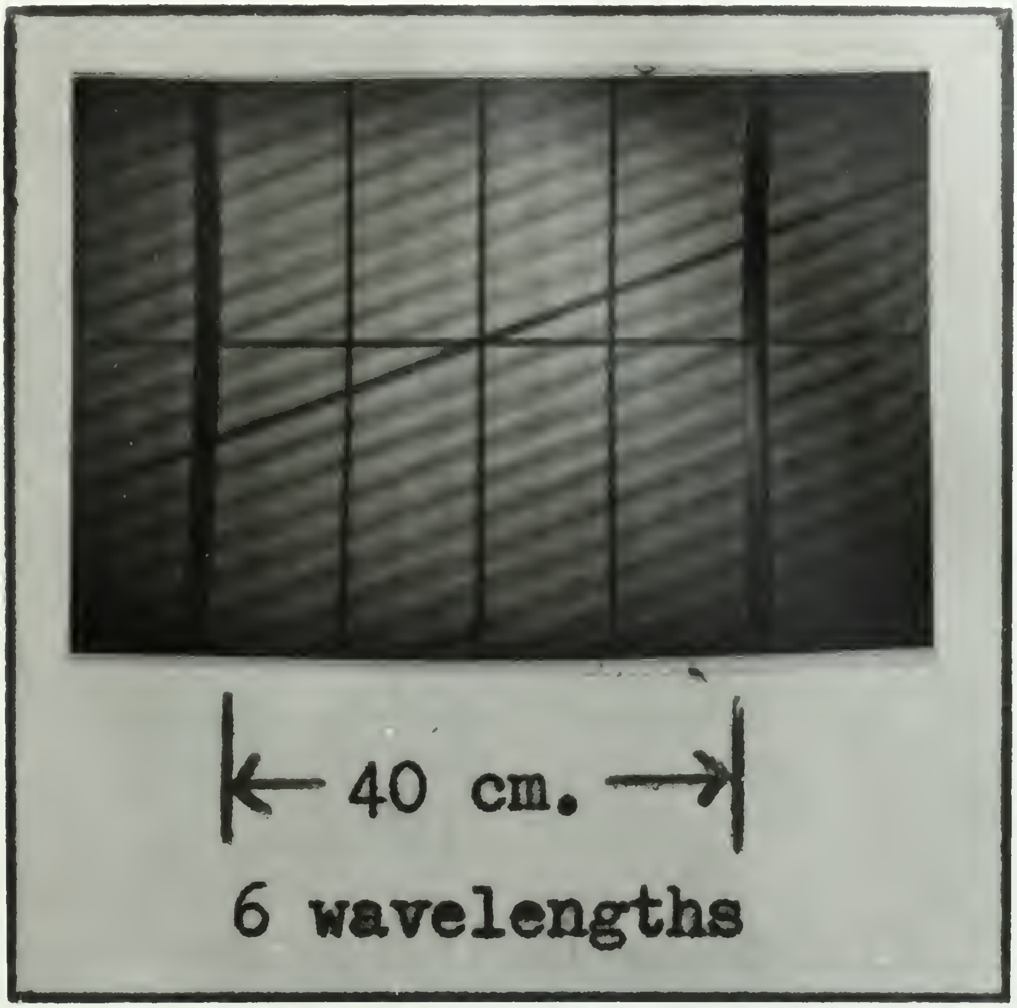

Figure 8 - Rotating mirror Photograph illustrating the method of analysis. The distance between the two heavy black vertical lines is 40 cm. and represents 6 wavelengths. The angle between the horizontal line and the striation is 21°. For a mirror rotational speed of 252 RPM and a tube to mirror distance of 78 cm., this angle represents a striation velocity of 107 meters/sec. The frequency then is 1605 $sec.^{-1}$

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necessary to calculate the frequency from knowledge of the velocity and wavelength of the moving striations using the relation, $v = \lambda \nu$ where v is the velocity, λ is wavelength and ν is frequency. As described previously it was necessary to analyze rotating mirror photographs to measure the moving striation wavelength for an unstable discharge. From these same photographs the velocity can be determined.

2.8 Velocity Measurements

For a stable discharge the velocity was determined from the product of frequency and wavelength. For the unstable discharge the velocity was calculated from rotating mirror photographs using the following scheme:

(1) $\Delta x = v_s t$

(2) $\Delta y = 2R\omega t$

(3) $\dfrac{\Delta y}{\Delta x} = \tan \theta = \dfrac{2R\omega}{v_s}$

(4) $v_s = 2R\omega \cot \theta$

R = tube to mirror distance (55 cm for all photographs analyzed)

$\omega = 2\pi$ (revolutions per second) $= \dfrac{2\pi N}{60}$ sec

Striation velocity $= 11.5\ N \cot \theta \ \dfrac{\text{cm}}{\text{sec}}$

A comparison of the values of velocity determined by the different methods described indicate reasonable agreement. The percentage difference generally was less than ten percent.

3. OBSERVATIONS

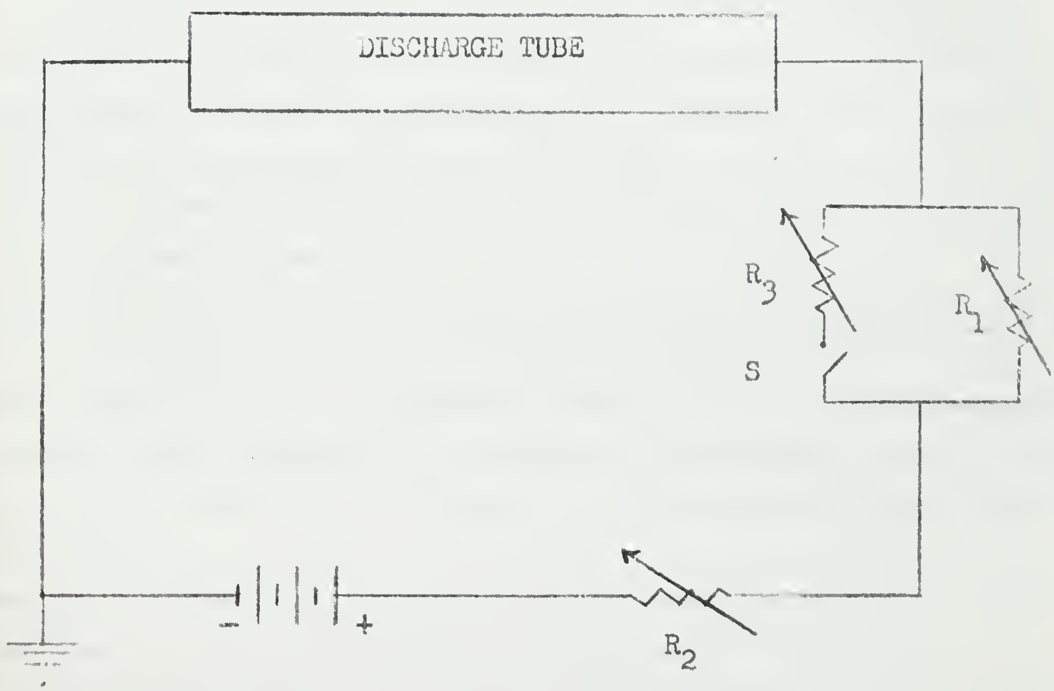
3.1 Background

This investigation was initially undertaken to gain more knowledge about the lower transitional region between a steady non-striated gas discharge and a gas discharge with fully developed moving striations. As reported by Pekarek (17) it is possible for a non-striated positive column to exist in a gas discharge at low currents and pressures. Figure 2 is a reproduction of Pekarek's experimental observations at low currents and pressures in a neon glow discharge. The first phase of this investigation was oriented toward finding similar results for an argon discharge. It was thought that a non-striated region would exist at the lower currents and pressures for this particular tube since previous studies performed by Cooper (28) using a tube which was similar indicated the existence of such a region.

Once this lower non-striated region was found, a study was to be made to determine what would happen in the gas discharge when the current was rapidly changed from values where there were no striations to values where striations should exist. A current pulser, incorporating a power pentode and designed by Cooper, was to be utilized. The current pulsing was to be done under conditions of constant pressure. The equivalent circuit for the electrical circuit with the pulser incorporated is shown in Figure 9. The multivibrator of the pulser is represented as a switch, and the power pentode is shown as a variable impedance. The resistors, R_1 and R_2, are variable resistors in the external circuit.

The criteria established for determining the existence of a non-striated positive column were that no potential nor light intensity fluctuations across the discharge tube should be seen on the oscilloscope and no striations should be seen on the rotating mirror.

Pressures varying from about 200 microns of mercury to 11 mm of mercury, and currents varying from 25 ma down to 0.13 ma were investigated. The region described was investigated using both hot and cold cathodes either with or without a Pupp anode. The Pupp anode was modified to operate at high voltages and low currents. The technique of operating the auxiliary discharge at high voltages and low currents was developed by Habermehl and Hughes (30).



EQUIVALENT CIRCUIT WITH CURRENT PULSER

Figure 9

During the course of the investigation all attempts to achieve the non striated pattern were unsuccessful. Although it was possible to obtain conditions so stable that light intensity oscillations indicative of moving striations could not be detected by the photomultipliers, moving striations were always detectable with the rotating mirror, although in some cases it was necessary to grearly increase its rotational frequency.

When it became apparent that moving striations were always present in the regions of pressure and current investigated, the investigation became pointed toward a further study of some interesting phenomena that had been observed earlier in the experiment. It had been previously observed that the pattern of the striations sometimes became quite complicated. In certain ranges of pressure and current, waves, which shall be referred to as streaks, were detected that seemed to be moving from the cathode to the anode. These streaks, which were detectable and definable in rotating mirror photographs, could not be defined with a photomultiplier. As seen in a rotating mirror photograph the streaks appear to interact with the normal striations, slowing them down or, in some cases, actually stopping them for a finite period of time.

Another phenomenon which was probably similar to that observed earlier by Zaitsev (23) was detected at pressures below about 1.3 mm of mercury. At certain currents in this low pressure region two distinct, definable striation patterns moving from anode to cathode were detectable. Both of these patterns could be detected both in rotating mirror photographs and photomultiplier traces.

Some other interesting phenomena were also observed in the course of this investigation. It is the purpose of this report to describe these, as well as others mentioned earlier, with the photographs and plots found on the following pages.

3.2 Pressure versus Current Plot

In an attempt to facilitate the description of the various phenomena observed, the pressure versus current plot shown as Figure 10 has been divided into four regions. Although the actual region boundaries are not as definite as depicted, they are not arbitrary, but are based on the observed striation patterns. All the measurements were taken while steadily decreasing

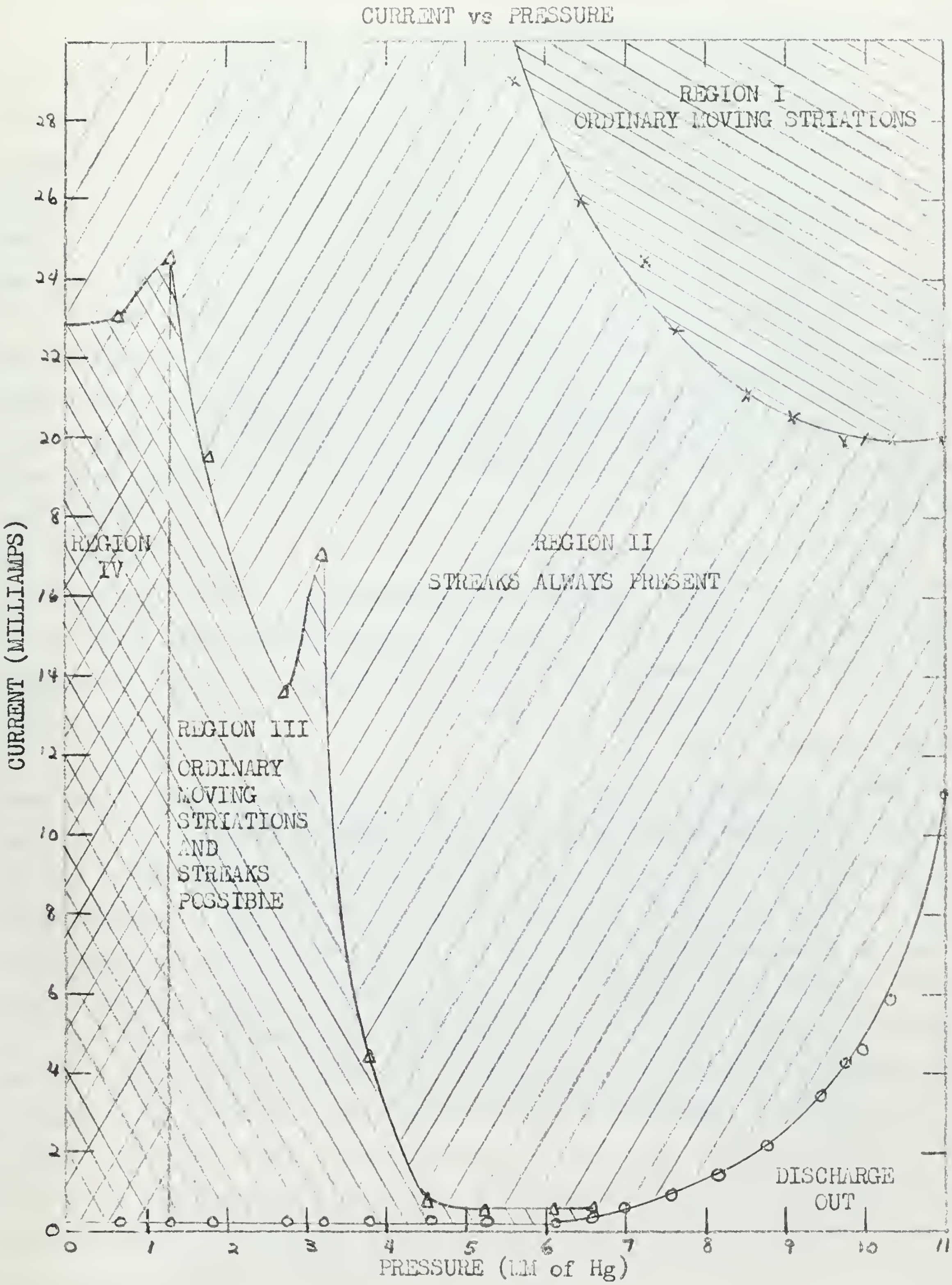

CURRENT vs PRESSURE
REGION I
ORDINARY MOVING STRIATIONS
REGION II
STREAKS ALWAYS PRESENT
REGION III
ORDINARY MOVING STRIATIONS AND STREAKS POSSIBLE
REGION IV
DISCHARGE OUT
CURRENT (MILLIAMPS)
PRESSURE (MM of Hg)
0
1
2
3
4
5
6
7
8
9
10
11
2
4
6
8
10
12
14
16
18
20
22
24
26
28

Figure 10

the current from 25 ma to tube cutoff to eliminate any hystersis effect such as that reported by Zaitsev (23) and Oleson and Found (31).

In region I of Figure 10 is found the normal moving striation pattern. The striations move from anode to cathode; they are stable; and their velocity, frequency, and wavelength are easily determinable. A photograph of the rotating mirror and a photograph of a photomultiplier output trace which are typical for this region, are shown in Figures 11 and 12. It should be pointed out here that in all rotating mirror photographs the cathode is at the right and time increases upward.

As the current is reduced slightly, the conditions in the discharge tube are altered so as to move into region II of Figure 10, and a new regime is encountered. Figures 13, 14, 15, and 16 show a series of photographs which illustrate the changes in the moving striation pattern as a transition is made from region I into region II of Figure 10. The previously straight and parallel lines representative of moving striations in the rotating mirror, are altered, indicating some new instability exists in the discharge. The oscilloscope trace of the photomultiplier output is no longer steady, and it is found impossible to obtain the single, continuous line trace characteristic of region I. As further penetration is made into region II, the effect of the instability in the discharge is seen to grow.

It is here in region II that the streaks which were mentioned earlier are seen. These streaks, which are quite evident in Figure 17, seem to indicate the movement of some disturbance from the cathode toward the anode of the discharge tube. Since time increases upwards and a horizontal line drawn through a rotating mirror photograph indicates the conditions in the discharge at a particular time, it is seen that this disturbance moving from the cathode to the anode slows the normal striations down whenever they meet. At times the rotating mirror photographs seem to indicate that the interaction time, between the normal striations and the streaks, lengthens sufficiently for standing striations to form, and standing striations are sometimes seen under these circumstances. If the slope of the streaks is interpreted as representing a velocity, an analysis of over 400 rotating mirror photographs, has revealed that streak velocity varies from almost zero to an almost infinite velocity.

Figure 11 - Typical striation pattern for region I. Rotating mirror photographs at discharge current 19.8 ma in argon at pressure 9.7 mm Hg. Mirror speed was set at 480 RPM.

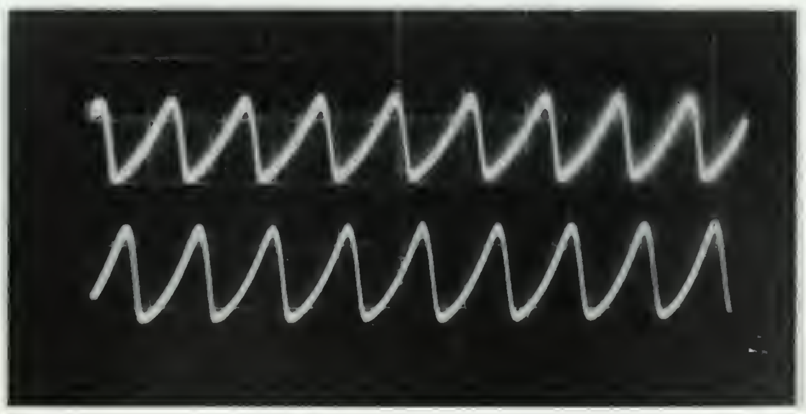


Figure 12 - Typical light intensity waveforms in region I. Discharge current 19.8 ma, pressure 9.7 mm Hg. in argon, time base 0.5 msec/cm, frequency 1732 $sec.^{-1}$, wavelength 4.73 cm. The upper trace corresponds to the anode photomultiplier.

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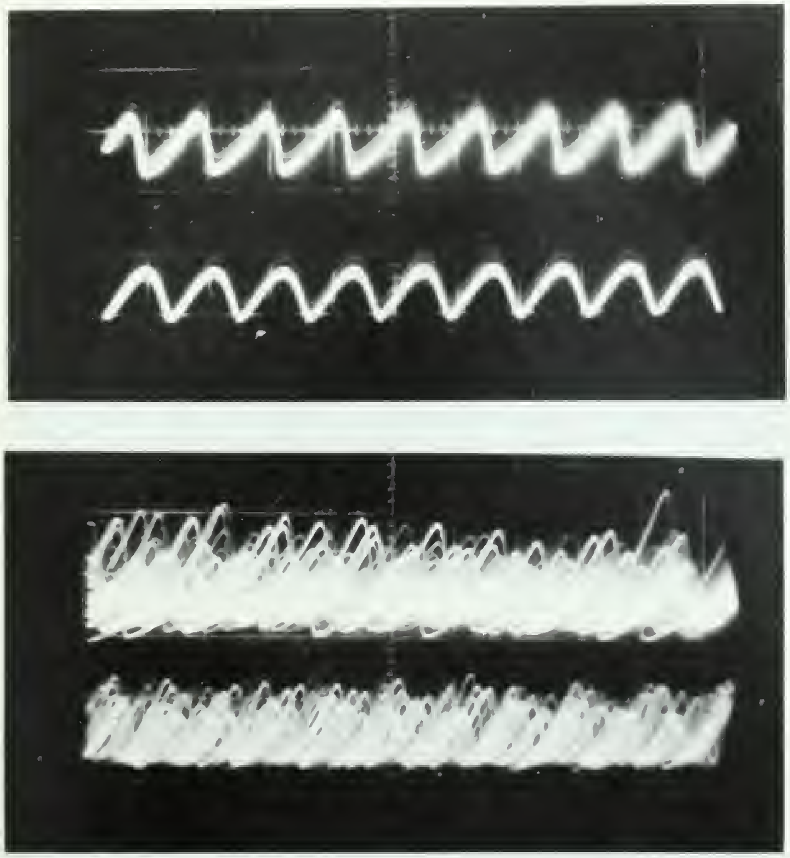
Region I

Current = 20 ma

Region II

Current = 17.5 ma

Figure 13 - Typical striation patterns for regions I and II. Rotating mirror photographs at pressure 10.8 mm Hg. of argon, mirror rotattional speed 480 RPM. Region I current was 20 ma and region II current was 17.5 ma.



Region I

ANODE

CATHODE

i = 20.0 ma

Region II

ANODE

CATHODE

i = 17.5 ma

Figure 14 - Typical light intensity waveforms in regions I and II. Pressure 10.8 mm Hg. in argon, time base 0.5 msec/cm, amplifier scale for both sweeps set at 0.5 mvolts/cm. The sweep was triggered by the voltage oscillations of the discharge tube for both photographs.

Region I - current 20.0 ma, frequency 1824 sec^{-1}, wavelength 4.63 cm.

Region II - current 17.5 ma, frequency and wavelength indeterminable.

Region I

Current = 24.5 ma

Region II

Current = 22.0 ma

Figure 15 - Typical striation patterns for regions I and II. Rotating mirror photograph at pressure 7.25 mm Hg. of argon, mirror speed 480 RPM. Region I current was 24.5 ma and region II current was 22.0 ma. Note the striations in region I starting to widen, indicating this pressure and current lie close to the boundary of the two regions. The exposure time was one second, so each photograph represents 8 mirror revolutions; but the pattern was very steady, and the appearance in the photograph is the same as seen with the naked eye.

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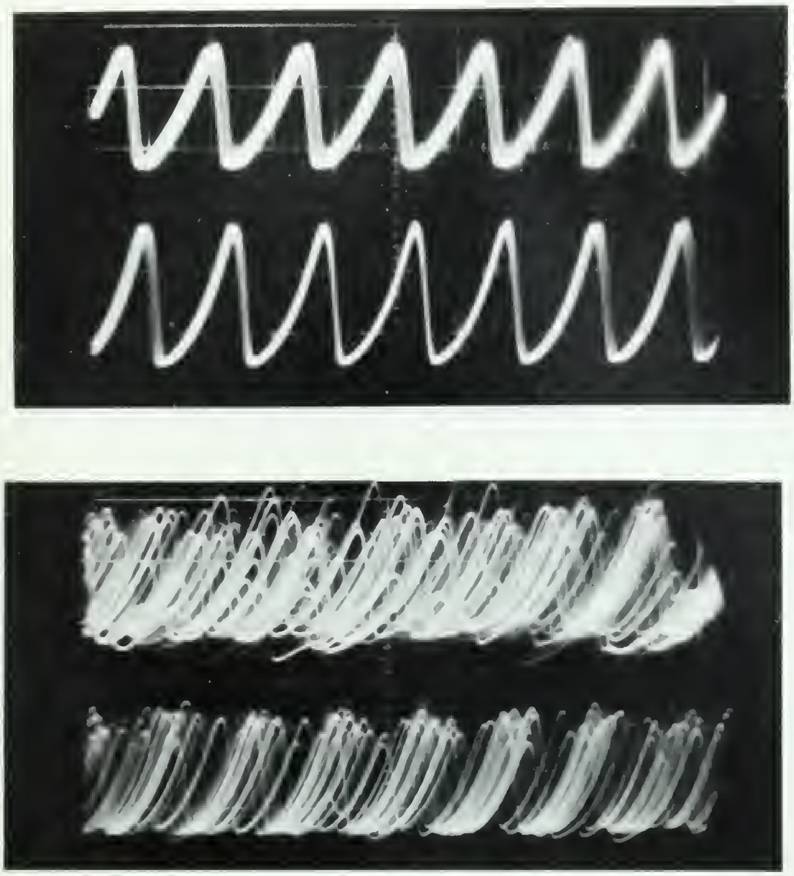


Region I

ANODE

CATHODE

i = 24.5 ma

Region II

ANODE

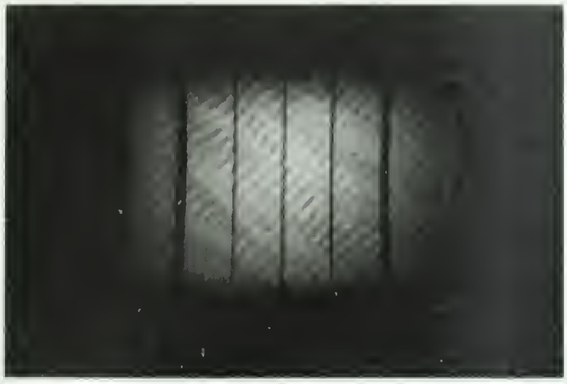
CATHODE

i = 22.0 ma

Figure 16 - Typical light intensity waveforms in region I and II. Pressure 7.25 mm Hg. in argon, time base 0.5 msec/cm, amplifier scale for both sweeps set at 0.5 mvolts/cm. The sweep was triggered internally by the cathode photomultiplier.

Region I - current 24.5 ma, frequency 1402 sec^{-1}, wavelength 5.30 cm. Note the trace for the anode is starting to split indicating this pressure and current lie close to the boundary of the two regions. This could be due to anode spots.

Region II - current 22.0 ma, frequency and wavelength are indeterminable.



p = 11.3 mm Hg.

i = 14.2 ma

p = 10.6 mm Hg.

i = 12.3 ma

Notice the apparent branching of streaks

p = 9.48 mm Hg.

i = 5.0 ma

Figure 17 - Typical patterns for region II. Rotating mirror photographs at various currents and pressures in argon. Mirror speed was set at 262 RPM. Note the change in the striation velocity as it interacts with the streaks. Note the streaks seem to be unaffected by the interaction.

The streaks which are quite obvious in a rotating mirror photograph could not be defined with the photomultipliers. It is surmised that the irregular appearance of the streaks prevents the photomultiplier from producing a stable oscilloscope trace. Using the rotating mirror photographs, attempts were made to show that the streaks were dependent in some simple way on the voltage, current, pressure, and other discharge parameters, but the analysis of the many photographs taken has indicated no simple connection between the random velocity of the streaks and any other parameter.

As further changes in pressure and current are made, it is possible to move into region III. In region III of Figure 10 it was possible to have either the instability observed in region II or the normal striation pattern seen in region I. Here again there appears to be no simple explanation of what to expect at a particular value for current and pressure. Without any intentional alteration of the external conditions these streaks appear and disappear sporadically, i.e., the discharge is intermittently stable, producing the normal striation pattern, or unstable, producing the streaked pattern. A hysteresis effect, similar to that described by Oleson and Found (31), is also observed. It is also in this region that standing striations are first visible in the tube. As reported by Pigg, Burton, and Oleson (32), as the current is decreased at a given pressure under stable discharge conditions, the standing striations become more diffuse. Figure 18 illustrates the appearance of the standing striations in a rotating mirror photograph.

Still another regime with specific characteristics exists in certain current ranges for pressures below about 1.3 mm of mercury. In region IV double striation pattern, may exist. Figures 19 and 20 show rotating mirror photographs and photomultiplier waveforms to illustrate this latter phenomenon. The matched photographs were taken with the same conditions existing in the tube and the two distinct striation patterns have velocities, frequencies, and wavelengths which are measureable. The characteristics of the double striation pattern show no simple relation between the two patterns. Although there is a two to one ratio between the wavelengths of the striations at times, this simple ratio does not always exist.

Two rotating mirror photographs taken at a pressure of 750 microns are also quite interesting. These photographs are shown in Figure 21. The two photographs were taken under exactly the same tube operating conditions, the

p = 3.22 mm Hg.

i = 12.0 ma

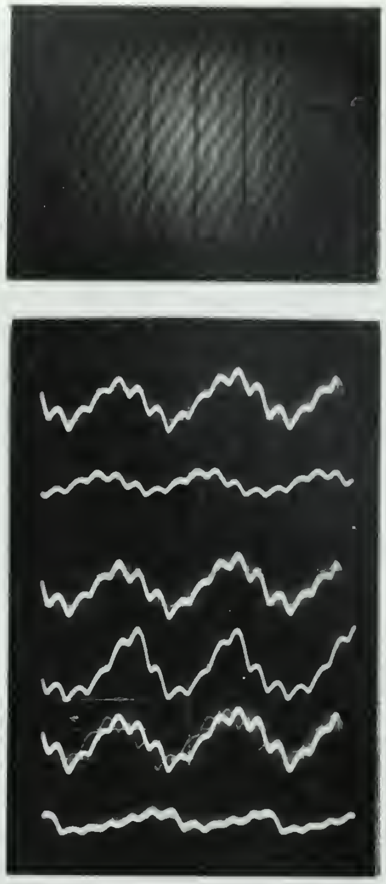
p = 3.83 mm Hg.

i = 3.0 ma

Figure 18 - Typical pattern for region III with standing striations in the tube. Rotating mirror photographs at different currents and pressures. Mirror rotational speed for both photographs was set at 262 RPM.

Rotational Speed 200 RPM

Rotating Mirror Photograph



Anode
Anode
Anode
Mid-tube
Anode
Cathode

Light Intensity Waveforms

Time Scale 0.5 msec/cm.

Frequency $3000\ \mathrm{sec}^{-1}$

Triggered Internally by the Anode Photomultiplier

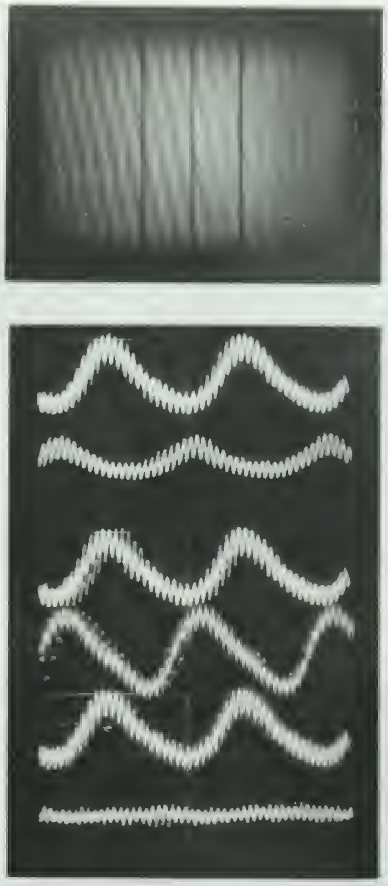
Figure 19 - Double striation pattern for region IV. Rotating mirror photograph and light intensity waveforms at pressure 0.87 mm Hg. in argon, current 24.5 ma.

The two sweeps show different amplitudes at the anode because they were equalized with the traveling photomultiplier at mid-tube where the light intensity is the greatest. The amplitude of the traveling photomultiplier sweep illustrates this difference in light intensity at three positions along the tube. A comparison of the double striation pattern is given below:

	Frequency	Wavelength	Velocity
Fast Wave:	$3000\ \mathrm{sec}^{-1}$	6.19 cm.	186 m/sec
Slow Wave:	$555\ \mathrm{sec}^{-1}$	3.12 cm.	17.3 m/sec

Rotational Speed 250 RPM

Rotating Mirror Photograph



Anode

Anode

Anode

Mid-tube

Anode

Cathode

Light Intensity Waveforms

Time Scale 1.0 msec/cm.

Frequency 4650 sec^{-1}

Triggered Internally by the Anode Photomultiplier

Figure 20 - Double striation pattern for region IV. Rotating mirror photograph and light intensity waveforms at pressure 0.4 mm Hg. in argon, current 23.5 ma.

The two sweeps show different amplitudes at the anode because they were equalized with the traveling photomultiplier at mid-tube where the light intensity is the greatest. The amplitude of the traveling photomultiplier sweep illustrates this difference in light intensity at three positions along the tube. Note on the rotating mirror photograph the very slow wave pattern is preceding from the cathode to the anode. A comparison of the double striation pattern is given below:

	Frequency	Wavelength	Velocity
Fast Wave:	4650 sec^{-1}	6.68 cm.	312 m/sec
Slow Wave:	225 sec^{-1}	3.38 cm.	- 7.6 m/sec

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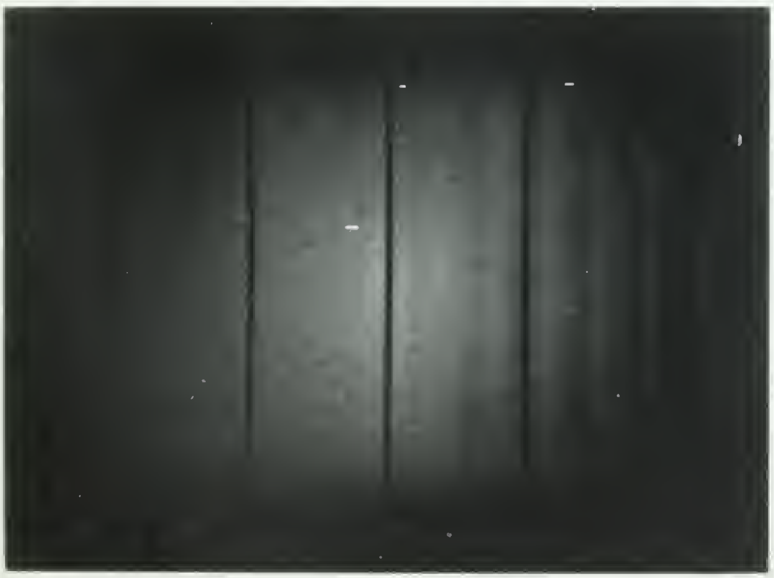
(a)

N = 255 RPM

v = 17 meters/sec.

Anode to the left



(b)

N = 2972 RPM

v = 680 meters/sec.

Anode to the left

Figure 21 - Rotating mirror photographs of the striation patterns in two sections of the discharge tube. Taken at pressure 750 microns of Hg. in argon, current was 1.3 ma. Note the apparent disappearance of the striations toward the anode of picture (a) and how increasing the mirror speed made the striations definable in picture (b).

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only difference being the speed of the rotating mirror. In the upper photograph the mirror had a speed of 255 revolutions per minute and in the lower photograph a speed of 2,972 revolutions per minute. What appeared to be a uniform light intensity pattern toward the anode in the upper photograph was in fact formed by striations of a much higher velocity. The velocity of the slow waveform was 17 meters per second while the fast moving striation had a velocity of 680 meters per second. As observed in the lower photograph, the increased mirror speed made this high velocity striation pattern definable and it brought the obvious striations in the upper picture to a near vertical position as expected. The two photographs indicate that the two distinct striation patterns do not necessarily exist throughout the entire tube, but can exist in various parts of the tube at the same time. This was also found by Cooper and Oleson (33) and reported at the Munich Conference in 1961. However, their observations were made while using a tube with several different diameters, so it is difficult to draw an analogy between their observations and the striation velocity pattern in this report.

Still another phenomenon which is similar to that reported by Coulter (25) was observed at currents about 1.0 ma Figure 22 is a rotating mirror photograph showing the observed striation pattern. This photograph shows alternate light and dark horizontal bands which indicate the tube is pulsing on and off, although the light bands are very complex revealing perhaps the presence of standing striations throughout the tube. It does not seem reasonable that this pulsing is the same as that reported by Coulter since his published photograph was taken with a discharge current of 360 ma. The pulsing was observed several times during this investigation; but whenever it was observed, the current was below 1.0 ma and the pressure was below 7.0 mm of mercury. It is not known whether the pulses are relaxation oscillations; it is quite possible the pulsing could be the result of capacitive effects in the electrical circuit. Unfortunately, because of the unpredictability of the pulsing and its sporadic nature when it was observed, a photograph of an oscilloscope trace of the photomultiplier output was never obtained.

From the preceeding description of the four regions of Figure 10, it should be clear that the complexity of the observable phenomena increased with decreasing pressure. Plots of the striation parameters, velocity, frequency, and wavelength, versus current and pressure, give further indications of the complexity of the glow discharge phenomena.

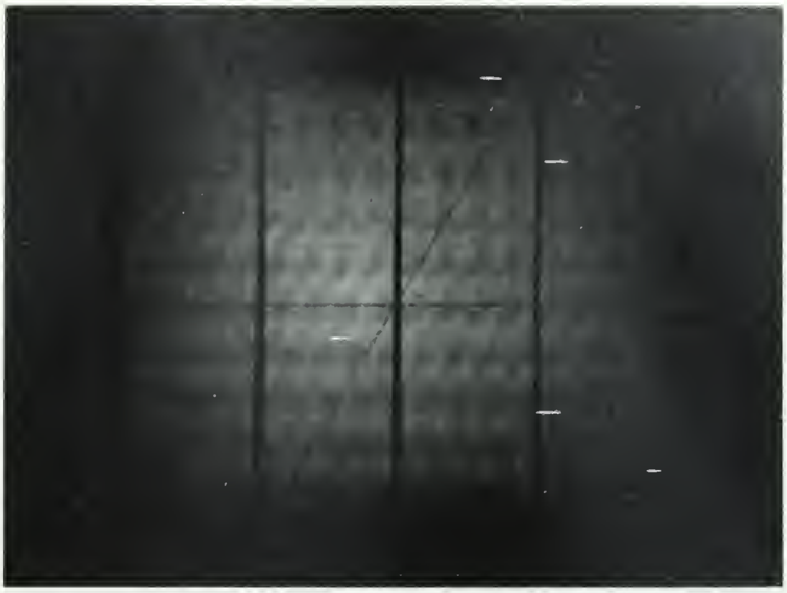
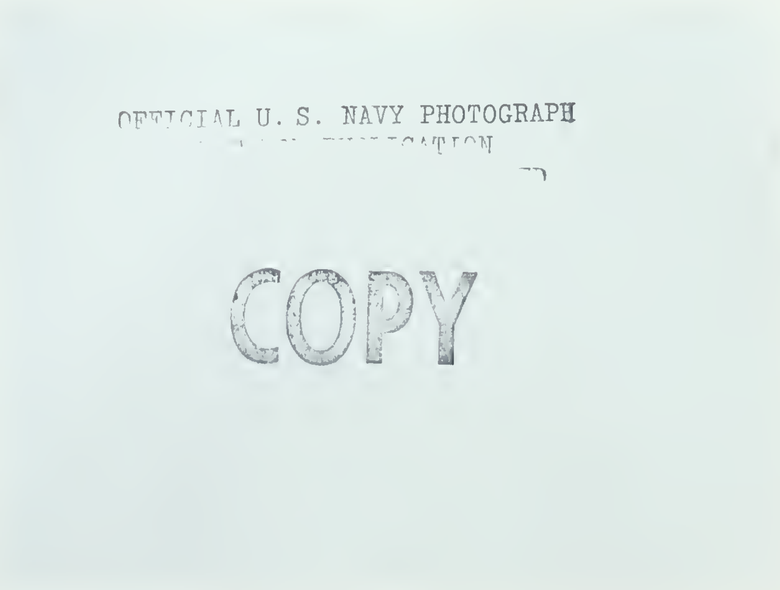


Figure 22 - Rotating mirror photograph of the typical pulsing pattern. Taken at 1.28 mm Hg. in argon, discharge current was 0.97 ma, mirror ratational speed was 254 RPM. The black line running through the center of the picture at an angle and the horizontal line running through the center portion are additional calibration marks.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3.3 Striation Parameters versus Current

A tube voltage versus tube current plot is shown in Figure 23. This voltage versus current plot is typical for a glow discharge over the range of conditions investigated (34). Plots of striation velocity, frequency, and wavelength versus current are shown in Figures 24, 25, and 26. These plots are constant pressure plots for pressures of 1.3, 5.2, 8.8, and 11.0 mm of mercury. These constant pressure plots were selected from approximately twenty such plots in the range from 0 to 11 mm of mercury because they best illustrate the observations in this pressure range. Some of the lines on the plots have discontinuities shown, indicating that there has been some radical change in the observable striation pattern.

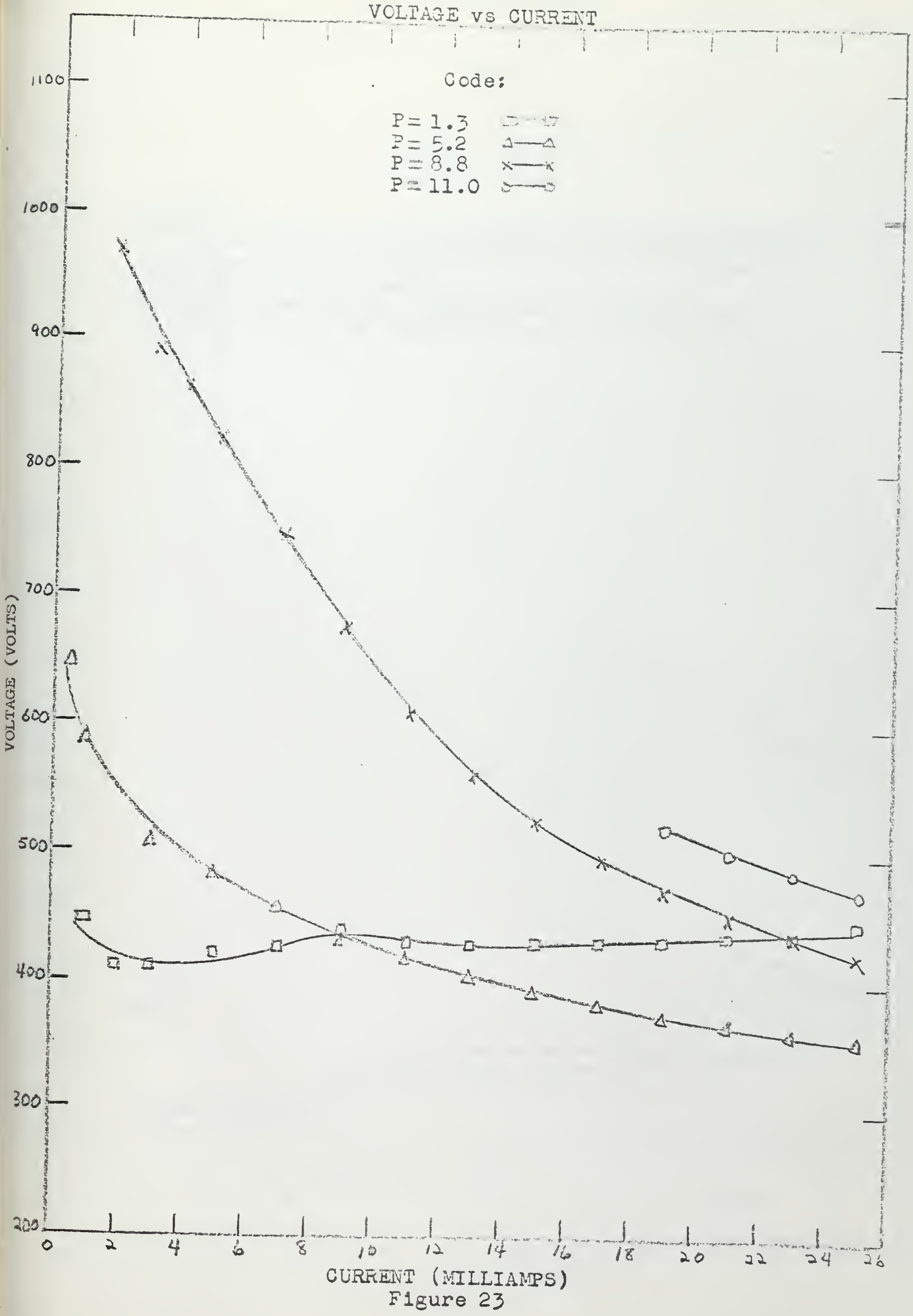
Starting at a pressure of 11.0 mm of mercury, the line shown ends at + 19.0 ma. The discharge at this pressure exhibited the normal striation pattern, and this was the only pattern observed until the discharge tube cut off. Recall that Figure 10 illustrates the striation pattern in this region with the cutoff current shown at 11 ma. The current flowing became extremely eratic just below 19 ma and was unreadable for a short period of time prior to cutting off, so the 11 ma current shown on Figure 10 is the result of an extrapolation from the lower values of pressure.

At a pressure of 8.8 mm of mercury a discontinuous line is shown indicating that a transition from region I, the regime of the normal striations, has been made to region II, the regime of streaks. Note that the appearance of the streaks results in a noticeable decrease in striation velocity.

It should be mentioned here that the velocity, frequency, and wavelength measured with streaks present are average values. Since it is impossible to use photomultipliers or a frequency counter for wavelength and frequency measurements when streaks are present, the only recourse is to analyze rotating mirror photographs.

A continuous line running the complete range of current investigated is shown for a pressure of 5.2 mm of mercury. This line is typical of region II where streaks are always present.

As pointed out earlier the most complicated striation patterns exist at pressures of about 1.3 mm of mercury and below. For a pressure of 1.3 mm of mercury streaks were observed in the range of current from 25.0 ma down


VOLTAGE vs CURRENT
Code:
P= 1.3
P= 5.2
P= 8.8
P= 11.0
1100
1000
900
800
700
600
500
400
300
200
VOLTAGE (VOLTS)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
CURRENT (MILLIAMPS)
Figure 23

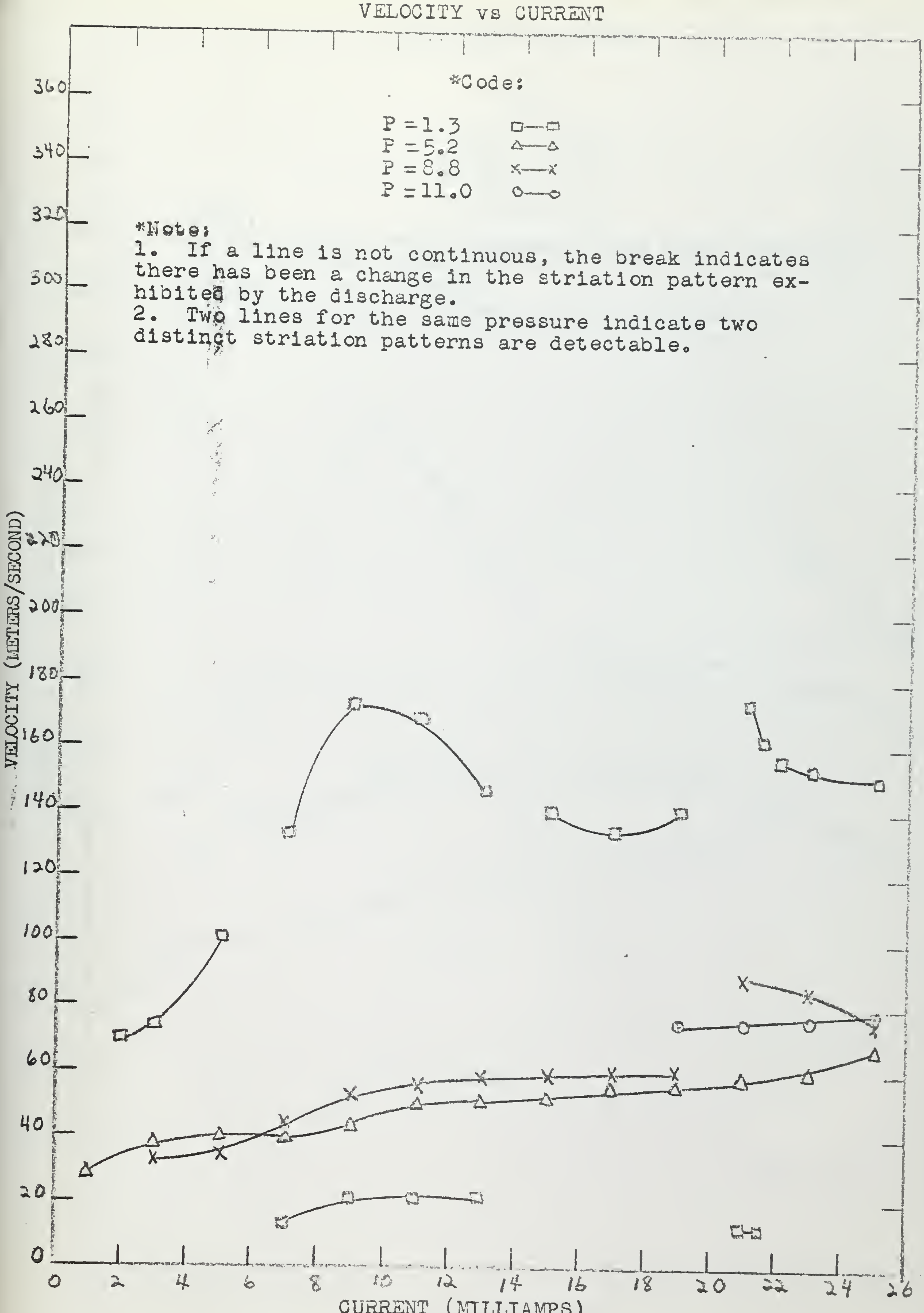

VELOCITY vs CURRENT
*Code:
P = 1.3
P = 5.2
P = 8.8
P = 11.0
*Note:
1. If a line is not continuous, the break indicates there has been a change in the striation pattern exhibited by the discharge.
2. Two lines for the same pressure indicate two distinct striation patterns are detectable.
VELOCITY (METERS/SECOND)
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
360
0
2
4
6
8
10
12
14
16
18
20
22
24
26
CURRENT (MILLIAMPS)

Figure 24

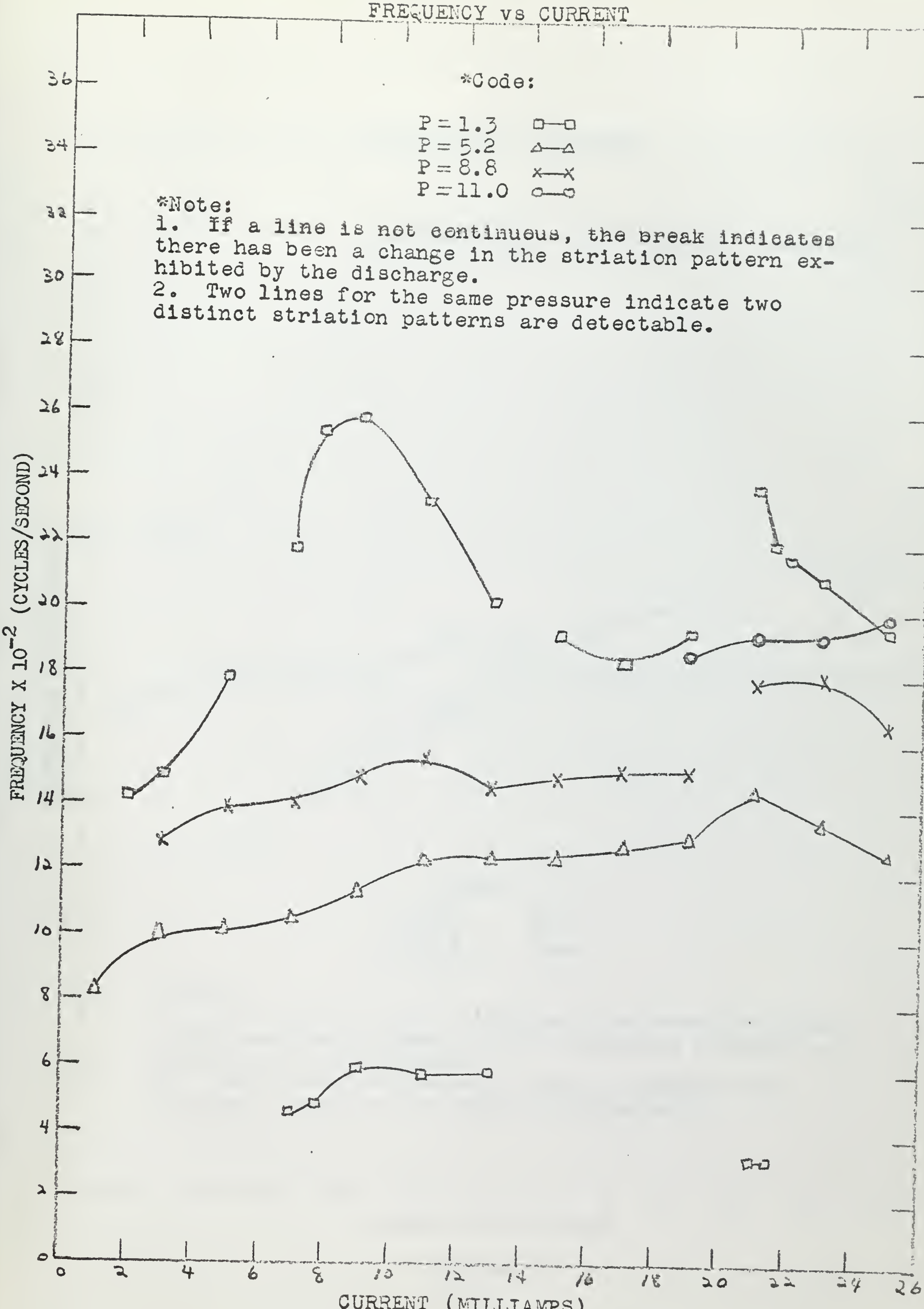

FREQUENCY vs CURRENT
*Code:
P = 1.3
P = 5.2
P = 8.8
P = 11.0
*Note:
1. If a line is not continuous, the break indicates there has been a change in the striation pattern exhibited by the discharge.
2. Two lines for the same pressure indicate two distinct striation patterns are detectable.
FREQUENCY X 10^-2 (CYCLES/SECOND)
CURRENT (MILLIAMPS)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36

Figure 25

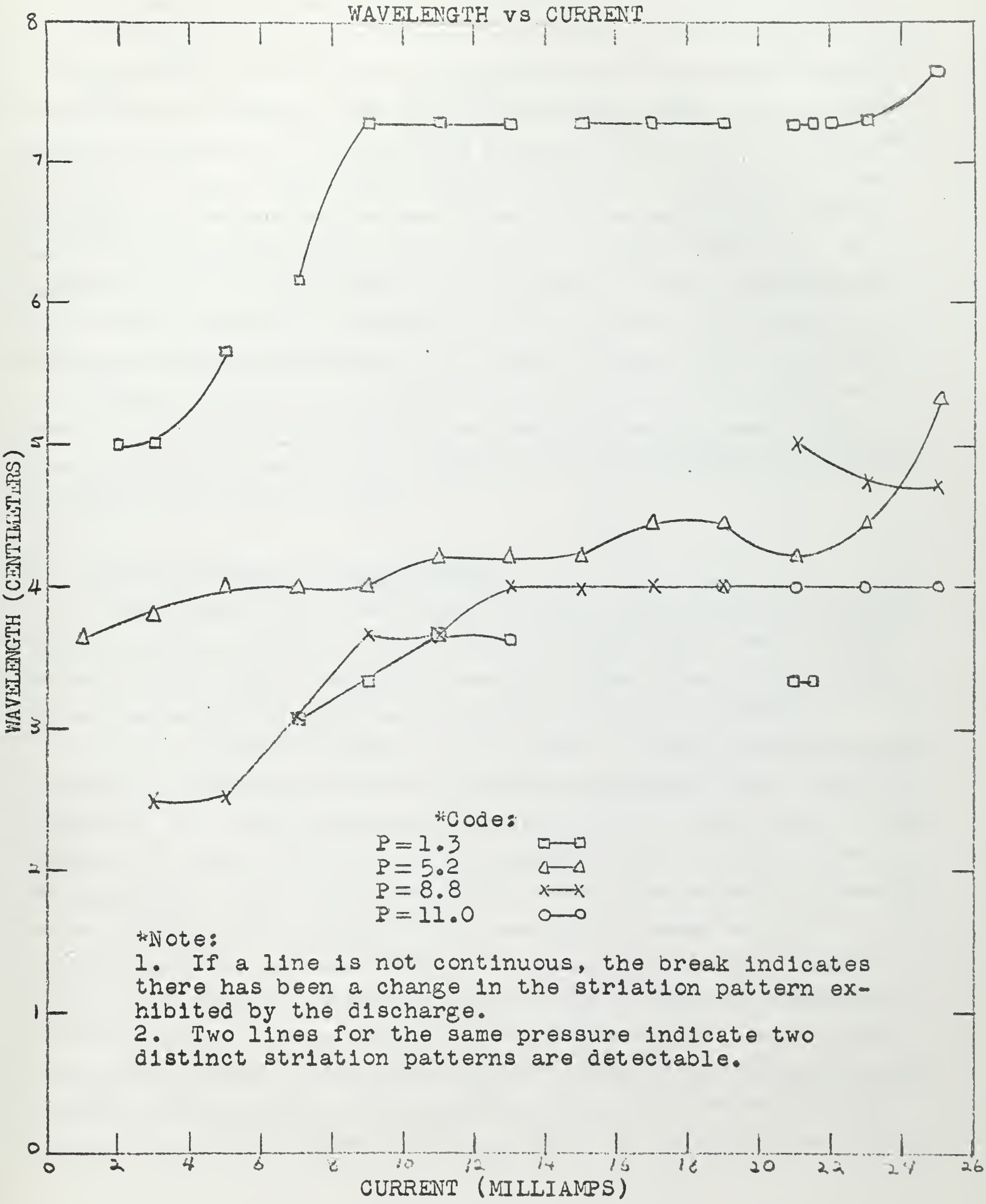

WAVELENGTH vs CURRENT
WAVELENGTH (CENTIMETERS)
CURRENT (MILLIAMPS)
0
1
2
3
4
5
6
7
8
0
2
4
6
8
10
12
14
16
18
20
22
24
26
*Code:
P = 1.3
P = 5.2
P = 8.8
P = 11.0
*Note:
1. If a line is not continuous, the break indicates there has been a change in the striation pattern exhibited by the discharge.
2. Two lines for the same pressure indicate two distinct striation patterns are detectable.

Figure 26

to 22.0 ma, and in this current range only one detectable striation pattern was indicated. Somewhere between 22.0 ma and 21.5 ma a change in the striation pattern occurred from the single detectable striation pattern to that exhibiting two distinct velocities, frequencies, and wavelengths. This striation pattern was short lived, existing only for the interval from 21.5 ma to 21.0 ma. Between 21.0 ma and 19.0 ma another change in the striation pattern was observed. Only the single frequency pattern was detectable from 19.0 ma to 15.0 ma. Here another change is observed. A return to the two distinct striation patterns was made between 15.0 ma and 13.0 ma. This double pattern persisted until the current had dropped below 7.0 ma. At currents below 7.0 ma the single striation pattern was again observed; but still another phenomena is seen with it. At a current below 1.0 ma the pulsing condition described earlier and shown in Figure 22 was encountered.

A study of the plots just described does not lead to any simple dependence of the velocity, frequency, or wavelength on the current. The plots, if anything, point to the complexity of the relationship between the striation parameters and current.

3.4 Striation Parameters versus Pressure

A tube voltage versus tube pressure plot for several values of constant current is shown in Figure 27. The constant current lines shown are representative of the range investigated, and the voltage versus pressure plot follows the same trend which has been observed by many experimenters.

Since an instability exhibiting the streaked striation pattern appeared to be the most common characteristic of the glow discharge in the range investigated, and since the data were normally taken for a fixed pressure while reducing the current; it was felt that continuous curves, representative of average values, would give more meaningful plots of the striation parameters versus pressure. Thus, Figures 28, 29, and 30, the respective plots of velocity, frequency, and wavelength versus pressure, are plots of average values of the striation parameters versus pressure. Only one constant current curve has been plotted because it is representative of the other constant current curves. Other constant current curves of the average velocity, frequency, and wavelength versus pressure show little if any vertical displacement from the line shown on the scale selected. Other constant current

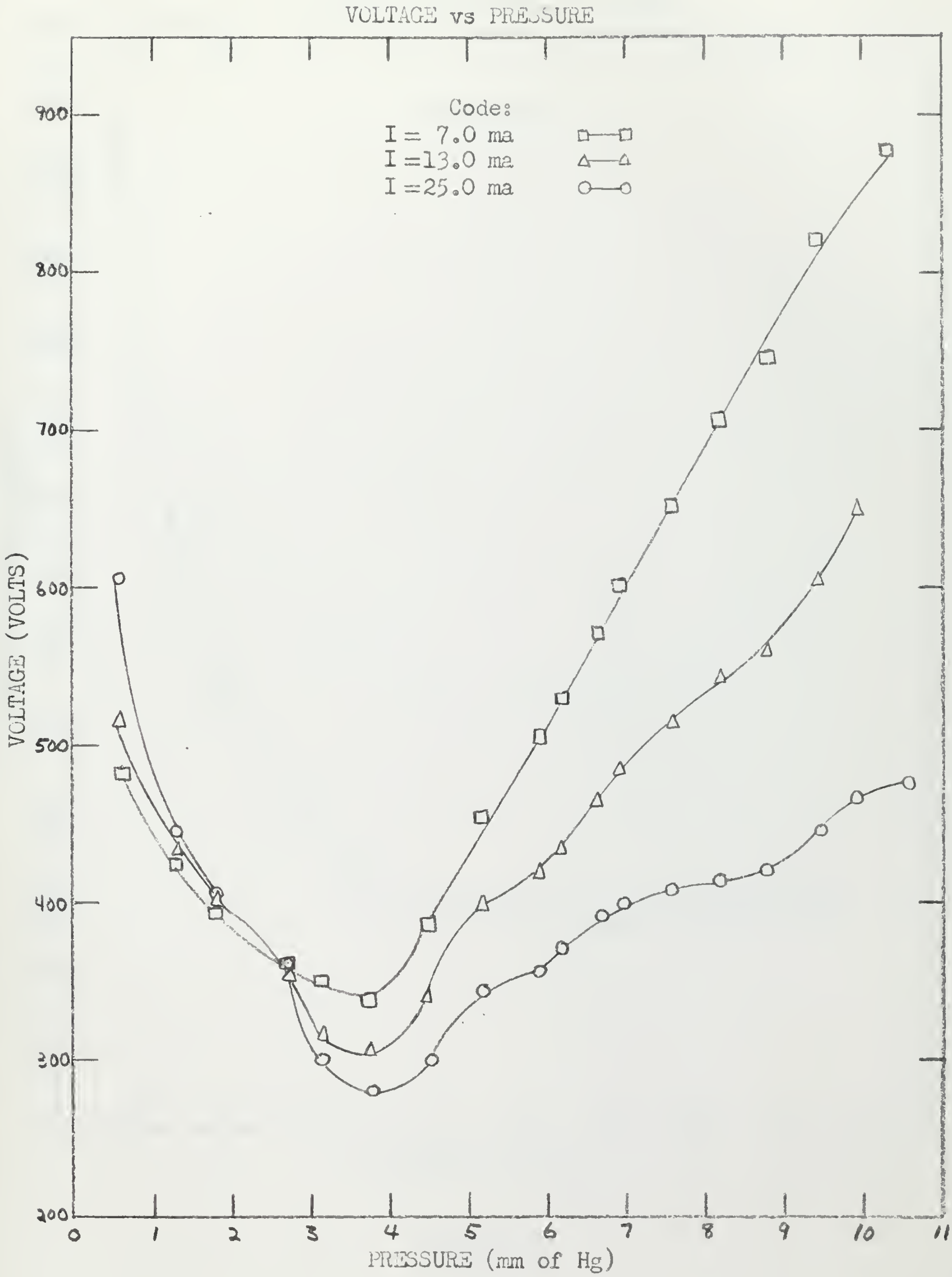

VOLTAGE vs PRESSURE
Code:
I = 7.0 ma
I =13.0 ma
I =25.0 ma
VOLTAGE (VOLTS)
900
800
700
600
500
400
300
200
0
1
2
3
4
5
6
7
8
9
10
11
PRESSURE (mm of Hg)

Figure 27

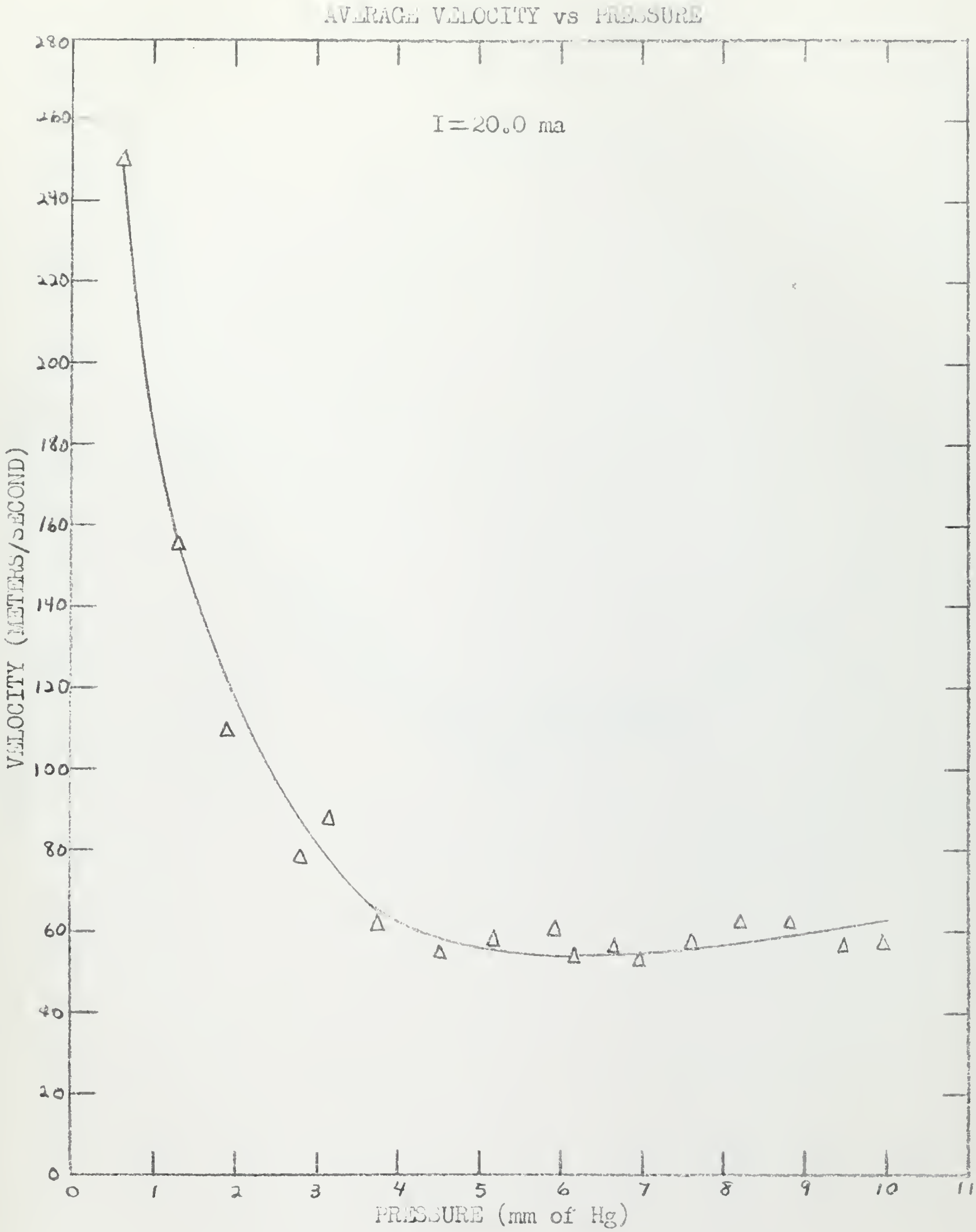

AVERAGE VELOCITY vs PRESSURE
I = 20.0 ma
VELOCITY (METERS/SECOND)
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
0
1
2
3
4
5
6
7
8
9
10
11
PRESSURE (mm of Hg)

Figure 28

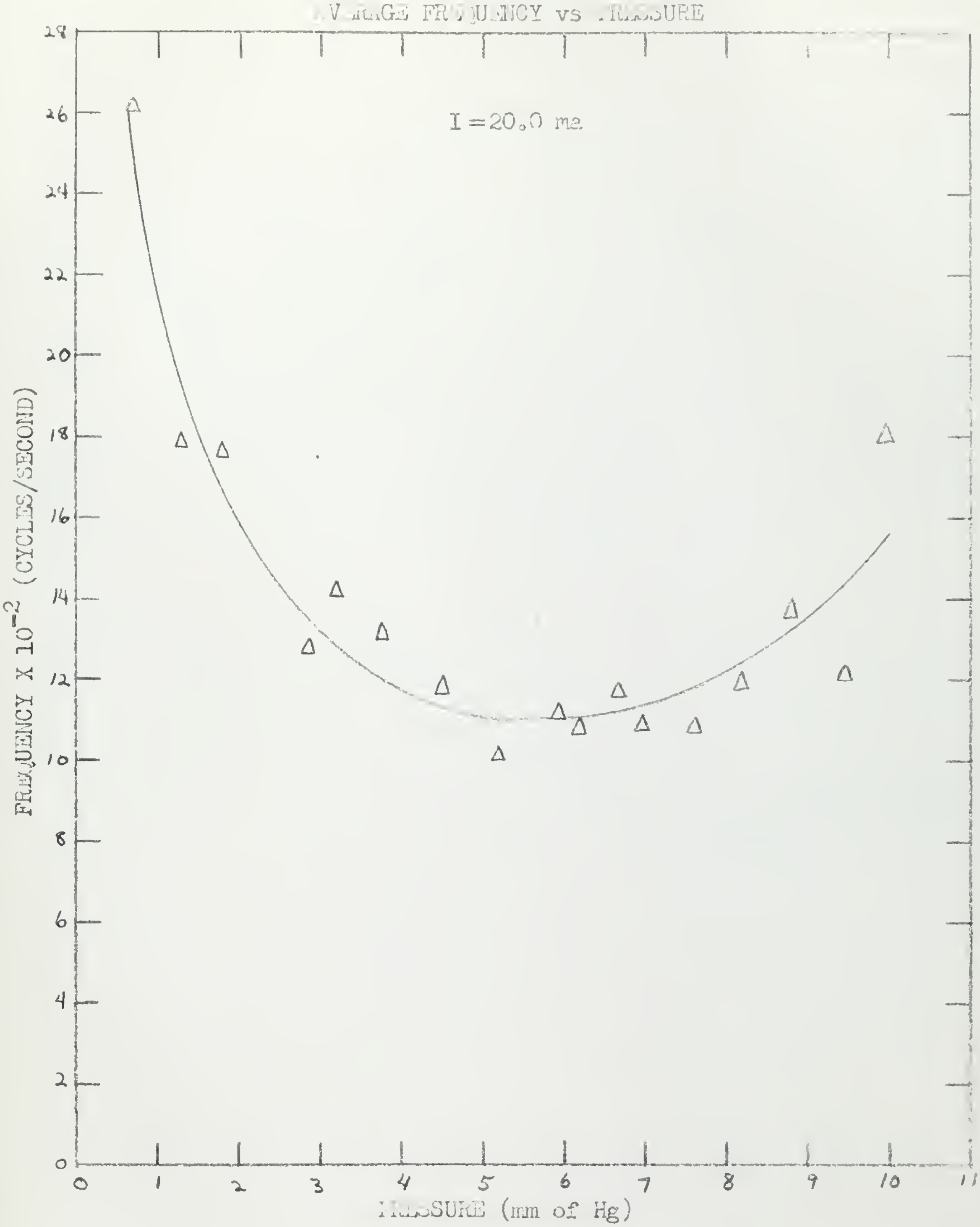

AVERAGE FREQUENCY vs PRESSURE
I = 20.0 ma
FREQUENCY X 10^{-2} (CYCLES/SECOND)
PRESSURE (mm of Hg)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
0
1
2
3
4
5
6
7
8
9
10
11

Figure 29

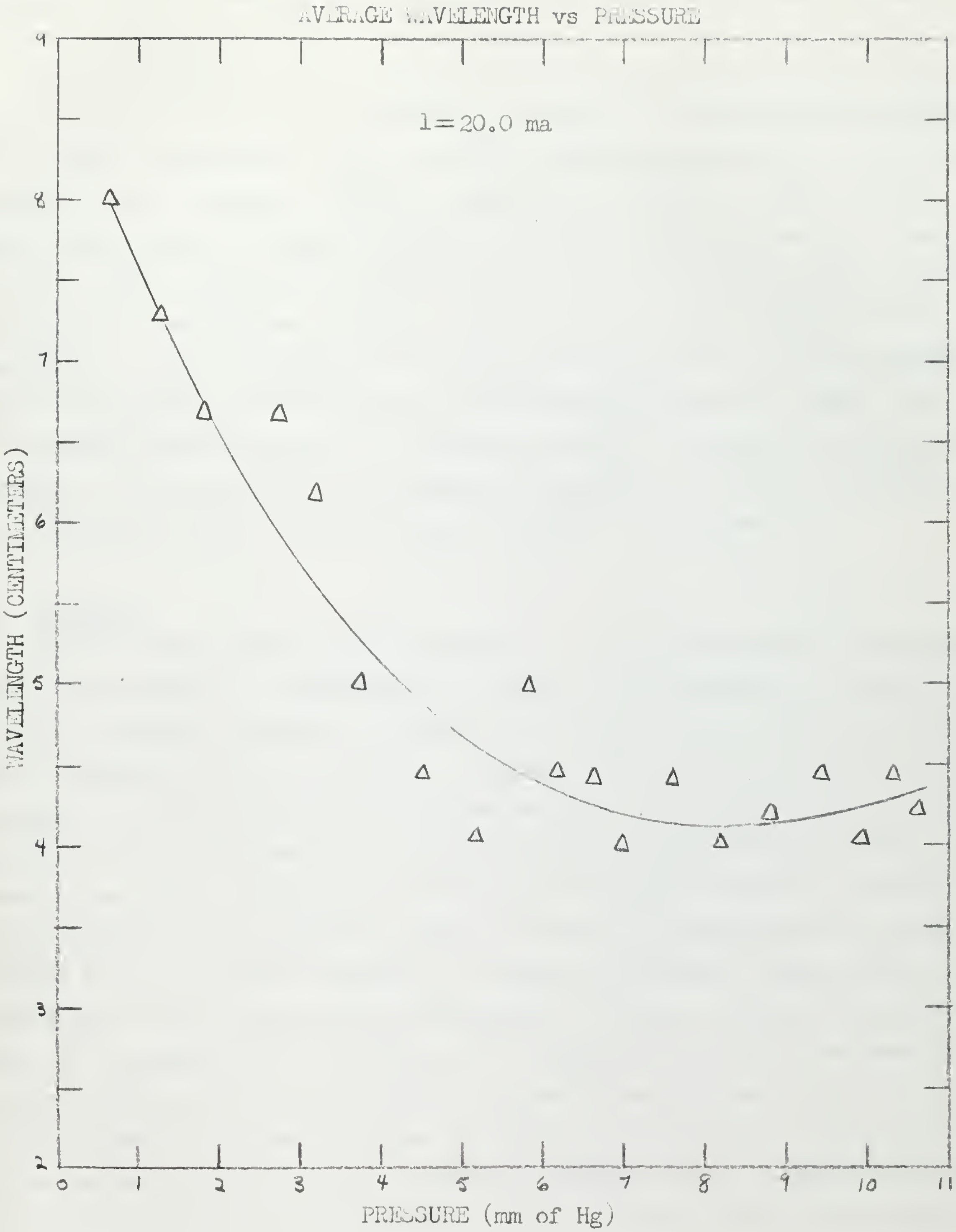

AVERAGE WAVELENGTH vs PRESSURE
I = 20.0 ma
WAVELENGTH (CENTIMETERS)
PRESSURE (mm of Hg)
9
8
7
6
5
4
3
2
0 1 2 3 4 5 6 7 8 9 10 11

Figure 30

curves, if plotted, would only serve to confuse the plots. The plots of average velocity, frequency, and wavelength versus pressure are similar to the results achieved by other investigators.

Many investigators have made plots of the log of the velocity of striations versus the log of the pressure in attempts to determine the dependence of velocity on pressure. A log velocity versus log pressure plot for several constant current values is shown in Figure 31. Generally, other investigators have obtained results which show velocity variations as 1/p to variations as $1/\sqrt{p}$. The plots shown in Figure 31, for constant current values of 5.0, 10.0, and 20.0 ma, exhibit slopes of -0.76, -0.65, and -0.60 respectively. If the striations were purely accoustic waves, it is expected that their velocity would decrease with decreasing pressure. Since, for any constant current value, the striation velocity increases with decreasing pressure, it is felt that the mechanism propagating the moving striation is of a different nature than that which propagates a sound wave.

3.5 Streaks

If the slope of the streaks appearing in the rotating mirror photographs can be interpreted as representing a velocity, it is possible to assign the streaks an average velocity. Although the pattern of the streaks as seen in the photographs is quite irregular at times, it was usually possible to determine an average slope for the streak pattern. Using the velocities determined from the photographs, plots of streak velocity versus current and pressure were made. These plots are shown in Figures 32 and 33. Plots of streak frequency and wavelength versus current and pressure were not made because it was virtually impossible to assign the streaks a meaningful wavelength due to their almost random appearance. Without wavelength measurements it was impossible to determine the frequency of streaks, because the photomultipliers could not produce a definable oscilloscope trace of the striation pattern whenever streaks were present in the tube. The velocity versus current plot for constant pressure was made using the same technique described previously for the normal striation velocity versus current plot.

*LOG VELOCITY vs LOG PRESSURE

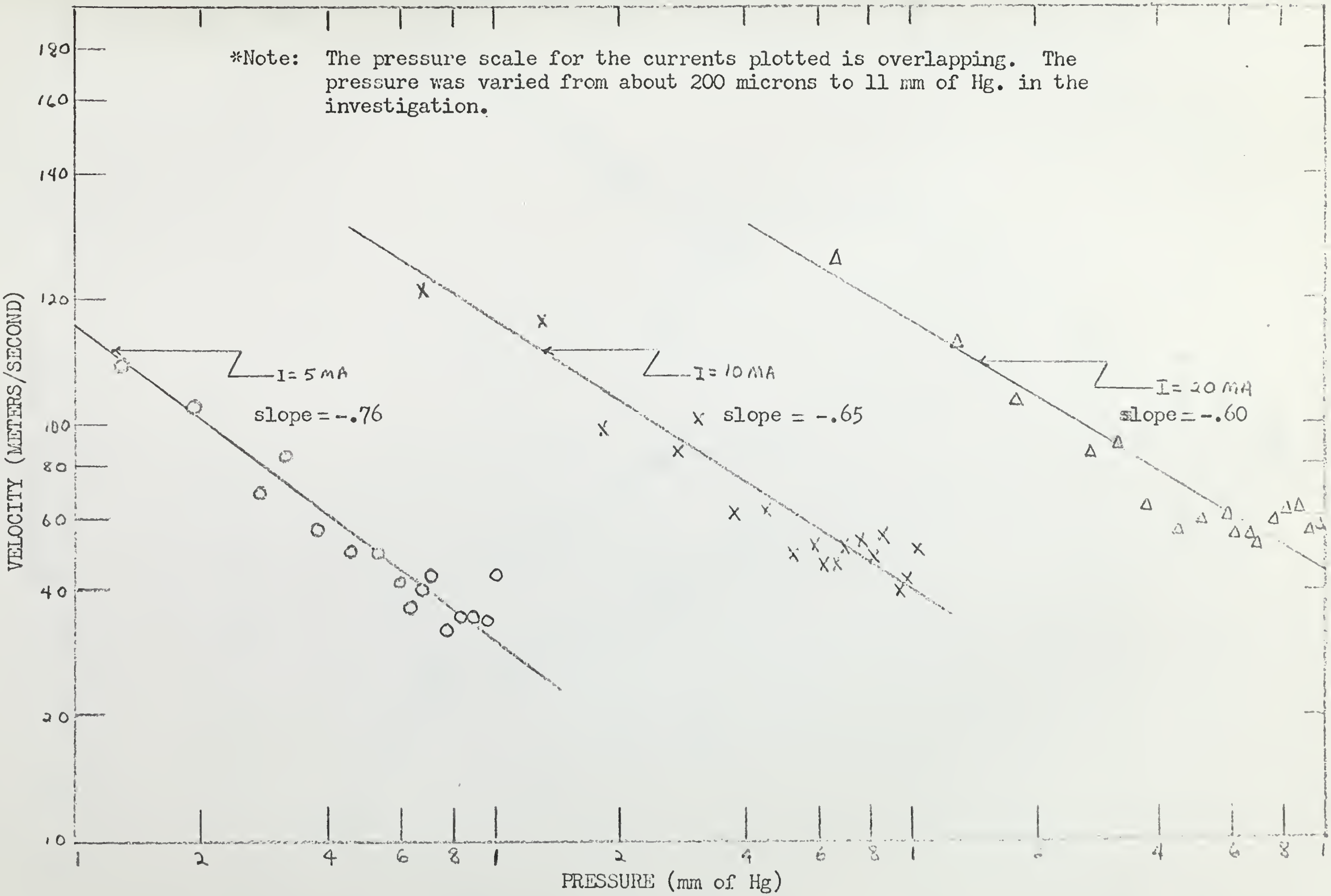


Figure 31

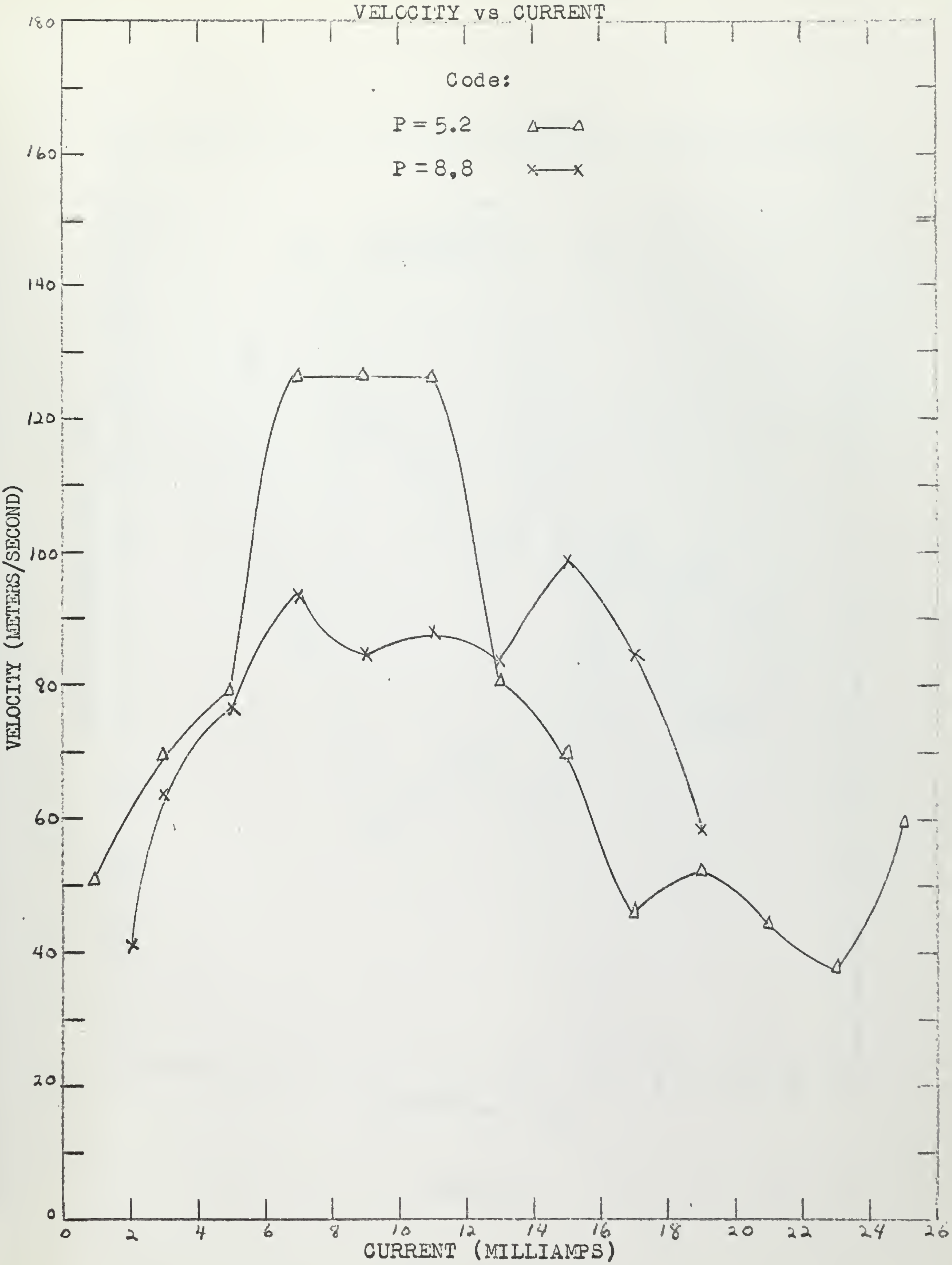

VELOCITY vs CURRENT
Code:
P = 5.2
P = 8.8
VELOCITY (METERS/SECOND)
CURRENT (MILLIAMPS)
0
20
40
60
80
100
120
140
160
180
2
4
6
8
10
12
14
16
18
20
22
24
26

Figure 32

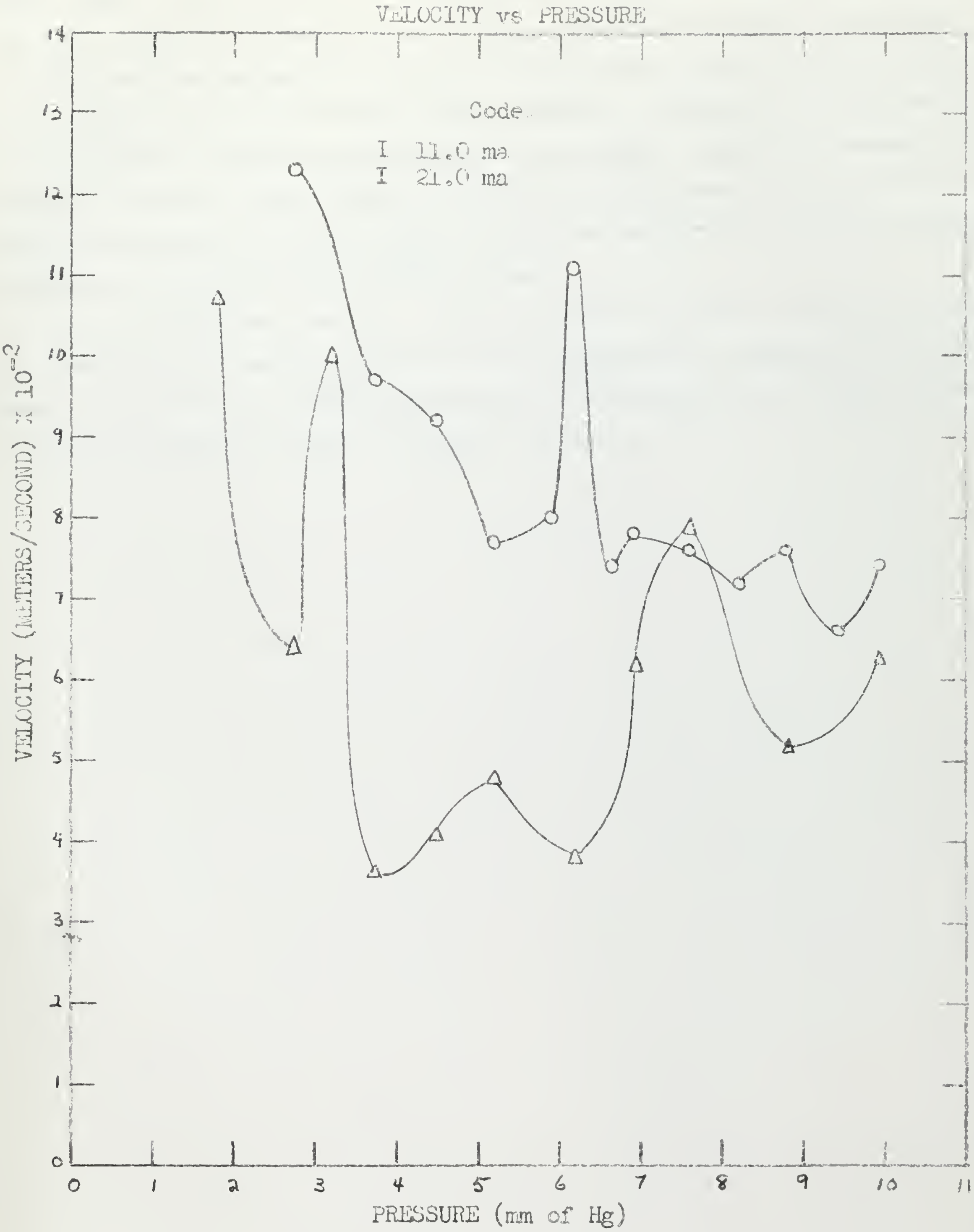

VELOCITY vs PRESSURE
Code
I 11.0 ma
I 21.0 ma
VELOCITY (METERS/SECOND) x 10^-2
PRESSURE (mm of Hg)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14

Figure 33

The appearance of the streak velocity versus current and pressure plots point again to the complexity of the glow discharge at low pressures and currents. There is apparently no obvious connection between the streak velocity and the pressure or current. The streaks do not have any recognizable periodicity but seem to be randomly excited. Although the streaks have a discernable slope in rotating mirror photographs suggesting movement from cathode to anode, their irregularity and the appearance of the plots of streak velocity versus current or pressure makes the assignment of even an average velocity to them have questionable value.

As commented upon earlier, there did seem to be some connection between the formation of standing striations and streaks, but changes from a streaked pattern to a pattern exhibiting standing striations occur so rapidly that no conclusive evidence exists to support the idea.

4. CONCLUSIONS

4.1 Conclusions

Based upon the experimental observations of Pekarek (17) and Cooper (28), a quiescent striation free state was expected in an argon glow discharge somewhere in the lower pressure and lower current region; but striations of some form were always present. All pressures from 11 mm of mercury to less than 200 microns of mercury and all currents from 25 ma to 0.13 ma were tested, and this failure to eliminate moving striations in the positive column can not be explained.

Moving striations are known to be dependent upon parameters such as tube geometry, electrode configuration, gas pressure, applied voltage, discharge current, and the type of gas present. In comparing this experiment with those of Pekarek and Cooper, which were discussed earlier in this report, Pekarek's results could have been due to a smaller tube diameter and a different type gas, while Cooper's results could be due to a shorter anode to cathode distance.

An analysis of the observations made in this investigation reveals, but does not explain, the complicated nature of the striation velocities in a glow discharge. Attempts to compare the experimental results with various proposed theories have been non-conclusive since they involved electron and ion densities and temperatures and other parameters which were not measured in this experiment. It is interesting to note that Gordeev's (4) theory requires that oscillations of some sort be present in the positive column for it to be stable. These oscillations, although not identified as moving striations, might then be necessary to sustain the discharge. This appears to be the situation in low pressure (5-50 microns of mercury) D-C discharges in gases such as argon and neon when high frequency plasma oscillations of the order of 500 megacycles are found (35).

Many of the phenomena observed in this investigation have been observed by others. Zaitsev (23) reported seeing two distinct striation patterns in his experiments with glow discharges in neon, neon-argon mixtures, and air. He did not report that it was possible for the two striation patterns to exist in different parts of the positive column simultaneously as was observed in this experiment. Coulter (25) photographed pulsations throughout

the discharge in a neon glow discharge. Pulsations were also observed in this investigation and photographed from a rotating mirror, but the pulsing phenomenon reported by Coulter is not necessarily similar to the pulsing observed during this experiment. Coulter was studying the high current effects and observed pulsing at 360 ma while the pulsing for this experiment occurred at a current of less than one ma and is probably a form of relaxation oscillation similar to that reported by Stansfield and Wise (36).

A large capacitor (2.5 millifarads) in series with a variable resistor was connected across the discharge tube in an attempt to eliminate the voltage oscillations. While observing the oscillations on an oscilloscope, the variable resistance was reduced. It was possible to diminish the voltage oscillations by a factor of about three before the discharge went out. This would appear to be another indication that possibly the oscillations are necessary to sustain the discharge.

Irregular disturbances, called streaks, which moved from the cathode to the anode were also observed. These streaks could be eliminated at the upper boundary of Figure 10 by placing a 10 henry inductor in series with the external resistance. By reducing the current to a lower value, however, it was always possible to arrive at a streaked condition where cutting the inductor in and out of the circuit had little or no effect. The streaks do not appear to be negative striations of the form described by Donahue and Dieke (6), Foulds (37), and others; because they could not be detected in the manner described by these authors, and the streaks had no simple dependence on any of the glow discharge parameters. In conclusion it seems that the streaks are a result of some instability at the cathode, but the exact role of the cathode in the production of streaks could not be determined.

5. RECOMMENDATIONS FOR FUTURE INVESTIGATIONS

5.1 Recommendations

Further attempts should be made to determine the origin and cause of the disturbance that moves from cathode to anode in low pressure, low current, argon glow discharges. This experiment suggested that different electrode materials and configurations as well as Langmuir probe techniques should be tried to isolate and study the cathode to anode traveling disturbance. Spectroscopic analysis of a gas discharge exhibiting the complicated striation patterns should also be made to determine whether or not the spectrum of radiation is the same for the streaked striation patterns as for the normal moving striation patterns. Preliminary measurements made in this investigation seem to indicate no difference. A study of the effects of a magnetic field on the streaked striation patterns should also be made.

If further attempts are made to find a non striated positive column in a low pressure, low current, argon glow discharge, it is suggested that a discharge tube of smaller dimensions be used, as indicated by the work of Pekarek. The smaller radius tube is suggested because of the well known dependence of striations on tube dimensions. After the non-striated positive column is located, a study can then be made to determine the effects of pulsing the current into and out of striated regions. It is also recommended that more work be done in the lower pressure region to investigate further the apparent reappearance of moving striations at greater mirror rotational speeds.

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Appendix I

A serious hazard was discovered during the initial phase of this investigation when a major effort was being made to achieve a high vacuum. A power failure occurred during the night when no one was observing the system. The power failure caused the diffusion pump and fore pump to stop, and a feature incorporated in the electronic circuits of the ion gauge prevented them from starting once the power was restored. Since the coolant in the cold traps was liquid nitrogen and since the system was at atmospheric pressure for some time, considerable liquid oxygen was manufactured in the inner portion of the cold traps. If the liquid nitrogen surrounding the liquid oxygen is removed, the rapid vaporization and expansion of the oxygen can produce an explosive force which is of such strength that it can completely destroy a vacuum system, but what is more important is that this explosive force can cause serious injury to any personnel in the vicinity.

In view of the above, it is felt that whenever liquid nitrogen traps are used on a vacuum system and a power loss of an unknown duration occurs, the only safe procedure to follow is:

1. Fill the liquid nitrogen traps
2. Energize the fore pump

As soon as the fore pump is energized, the pressure in the system will start to drop and permit the trapped oxygen to vaporize and to be removed from the system. After 10 to 15 minutes of pumping, all oxygen trapped will have been removed and the pressure in the system will start to drop. THEN AND ONLY THEN IS IT SAFE TO REMOVE THE LIQUID NITROGEN TRAPS. It is strongly recommended that this procedure be adhered to and that personnel working on vacuum systems be made cognizant of this hazard.